GENESIS OF A CLIMOSEQUENCE OF SOILS IN THE KOHALA REGION

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INTRODUCTION

The geographical and geological situations of the Hawaiian Islands offer a unique opportunity for the investigation of single-factor effects in the genesis of soils. Soils under 10 inches of annual rainfall are found within three miles of soils under 60 inches while the elevation, air temperature, rock composition, and geologic age remain fairly constant. Such an area, extending from the western to the northeastern side of Kohala Mountain, has been chosen for investigating a single-factor effect of climate, expressed as annual rainfall, on soil formation.

Trends of certain chemical, mineralogical, and physical properties with the average annual rainfall cannot easily be separated from trends associated with rainfall intensities. However, the isohyets of rainfall intensities for several specific periods of time, calculated by the United States Weather Bureau, correspond closely to the isohyets of annual rainfall.

In the tropics, the influence of climate can predominate over the effects of parent rocks, so that a single type of soil may be found over several different rock systems (Viswanath, 1944).

The influence of climate needs sufficient time to show its effects. In the Kohala region, the genesis of soils may have begun in the middle Pleistocene or earlier. The last volcanic eruptions are thought to have occurred during the middle Pleistocene (Stearns and Macdonald, 1946:183).

LITERATURE REVIEW

General comment:

The term "fairly constant", used in the introduction, needs to be emphasized. This literature review will consider possible variations in the Kohala region of four factors of soil formation. It will also include investigations in Hawaii and other tropical areas concerned with the effect of rainfall on soil properties, soil chemistry, and soil minerals.

Parent rocks:

Stearns (Stearns and Macdonald, 1946) has conducted the most recent geological and hydrological survey of the Kohala region. The mountain is mainly olivine basalt (Pololu volcanic series) capped mainly with oligoclase andesitic rock (Hawi volcanic series). Hawi rocks cover much of the shoreline between one mile south of Mahukona and Kawaihae. The northwestern slope is not affected except near the summit. The northern to northeastern slope is generally covered with Hawi rocks above approximately 1000 feet with tongues of rock extending almost to sea level.

On the north to northeastern slope, the two volcanic series were identified and mapped by Stearns partly on the basis of soil properties. The grayish, shallow soils supposedly indicate clinkery andesitic parent rock of the Hawi series, while the redder, deeply weathered soils indicate the Pololu series (Stearns

and Macdonald, 1946:179).

Wentworth (1938) investigated the volcanic ash areas of the Island of Hawaii. He considered the slopes of the Kohala Mountain to be lava as far south as Kawaihae.

Macdonald (1949), (also in Stearns and Macdonald, 1946: 189), presents a table of the principal rocks of the Island of Hawaii. The following descriptions are taken from that table:

Olivine Basalt

Texture:	Porphyritic, less commonly nonporphyritic
Phenocrysts:	Olivine, 0-20%, 1-8 mm long
	Plagioclase (Ab_{20}-Ab_{50}), 0-25%, 1-10 mm rarely as much as 25 mm
Groundmass:	Plagioclase (Ab_{35}-Ab_{50}), 25-45%
	A little interstitial andesine in alkalic basalt only
	Monoclinic pyroxene, 25-45%
	Olivine, 1-15%
	Both magnetite and ilmenite, 7-15%
	Apatite recognizable in a few specimens
	Some contain glass

Oligoclase Andesite

Texture:	Porphyritic or nonporphyritic
Phenocrysts:	Olivine, rare
	Plagioclass (Ab_{45}-Ab_{80}), 0-5%, 1-8 mm long
	Riebeckitelike amphibole, 0-1%, less than 1 mm long
	Basaltic hornblende, rare
Groundmass:	Plagioclase (Ab_{70}-Ab_{85}), 50-60%
	Monoclinic pyroxene, 15-30%
	Olivine, 1-8%
	Iron ore, mostly magnetite but some ilmenite, 10-25%
	Biotite, 0-2%
	Riebeckitelike amphibole, 0-1%
	Apatite, about 1%
	Hornblende, rare, 0-1%
	Some specimens contain glass

Andesine and oligoclase in Hawaiian rocks sometimes appear abnormal under the petrographic microscope apparently due to the presence of a small amount of potassium feldspar. This mineral is probably metastable at ordinary temperatures (Macdonald, 1942).

Time factor:

The Pololu eruptions probably occurred during the Tertiary period (Wentworth, 1938:171; Stearns and Macdonald, 1946:183; Macdonald, 1953). The Hawi eruptions may have occurred during the late Tertiary period (Wentworth) or during the early to middle Pleistocene periods (Stearns and Macdonald; Macdonald). Buried soils under the Hawi volcanic series indicate that a long period of time elapsed between the Pololu eruptions and the Hawi eruptions.

Even though rocks in other parts of the world may be older, soils derived from them may be geologically younger, if erosion or deposition is active, than those soils near the Kohala Mountain. On the drier slopes of the Kohala Mountain, erosion by water is slight. "The rough nature of their (the aa andesites) surface is not lost even when considerably weathered and covered with grass," (Stearns, 1946:179). Thornbury (1965:26) states, "Little of the earth's topography is older than the Tertiary and most of it no older than the Pleistocene." If this is true, then the soils on the drier slopes, at least, may be

considered to be among the geologically old soils of the earth.

Relief factor:

While time is a passive factor in soil genesis, relief is a modifying factor. In Juang (1965) on illite in a sequence of soils, elevation caused both rainfall and temperature to change. Part of the present objective of studying a sequence of soils around the Kohala Mountain is to determine the effect of rainfall in the formation of illite free of the effect of temperature changes.

In the tropics, at least, the effects of elevation cannot be ignored with respect to clay formation. An examination of 33 samples in southern India indicates that alumina, sesquioxides, silica, organic carbon, and base exchange capacity can be correlated with rainfall. The clay content, however, shows a significant increase with increasing elevation (Nair, 1962).

The relief factor of slope is very important in controlling the flow of groundwater and surface water. Laterite formation in a 35-inch rainfall zone of western Maui is attributed to groundwater from the 200-inch rainfall area at higher elevations. After a heavy rain in the higher elevations, water can be seen in an ordinarily dry well in an elevation below the laterite (Sherman, 1949). Usually, groundwater is not important as a soil-forming factor in Hawaii because of the permeable nature of most Hawaiian rocks (Cline, et al., 1955:13).

The stabilization of black soils under a 40-inch rainfall in the Saint Louis Heights area of Honolulu may be due to replenishment of bases through seepage waters from adjacent uplands (Uehara and Sherman, 1956).

Surface erosion depends upon relief, availability of the erosion agents, and characteristics of the soil. In the sample sites chosen for this thesis, there is probably some erosion by wind, but erosion by water should be very slight due to the specifically chosen sites. The sample sites are on the front edge of a slightly high microrelief with natural drainage to the right and left upslope from the sample sites.

Vegetation factor:

As pointed out by Juang (1965), vegetation is probably the agent by which potassium is recycled. Potassium is necessary for the formation of illite.

Of the soil samples collected near Kohala Mountain, the two wetter ones are now under sugar cane and the three drier ones are now under grass. From the silvicultural point of view, Whitesell (1964) classifies the area that includes the Hawi sample site, the Mahukona sample site, and almost the Kawaihae sample site as natural forest land with respect to the Koa tree.

Climate and soil mineral formation in the tropics:

"Weathering in Hawaii is largely a process of desilication," according to Bates (1960:35). He considers that glass weathers

more easily than olivine, which weathers more easily than plagioclase.

Bates (1960) believes that mica yields kaolinite and plagioclase yields halloysite. Potassium feldspars could yield kaolinite with mica as an intermediate product. Due to the absence or scarcity of mica and potassium feldspars, Bates reasons that kaolin in Hawaii should be predominantly halloysite. Saing (1964), in determining the type of kaolin along the Kipapa transect, has electron micrographs showing kaolinite to be dominant. The soil series with which Saing worked include three Low Humic Latosols, a Humic Latosol, a Humic Ferruginous Latosol, and the Koolau ceramic clay.

Work by Matsusaka and Sherman (Kanehiro and Chang, 1956:6) indicate that under a continuously wet state, aluminum oxides become the dominant end product, while under an alternating wet and dry climate, iron oxides become the dominant end product of weathering along with a high titanium oxide content.

Sherman and Uehara (1956) examined a boulder of olivine basalt weathering in soil under 20 inches of rainfall. Inside the boulder, olivine yielded montmorillonite, probably due to appreciable amounts of soluble magnesium present. At the outer edge of the rock, a mica-like mineral replaced olivine. Differential thermal analysis indicates the development of kaolin in the matrix. Outside the weathering core, the exfoliated layers contain kaolin

where drainage is good and under the boulder where the retention of bases is favored, montmorillonite forms.

Under 15 to 25 inches of rainfall, olivine basalt can yield a black earth containing montmorillonite or a red earth containing kaolin. Both black and red soils are found in Hawaii (Uehara and Sherman, 1956).

Several secondary minerals in soils form from solution. Carbonates are expected in arid soils. In certain semi-arid situations in Hawaii, dolomite forms depending upon drainage conditions (Sherman, et al., 1947). Oxides also form from solution as is indicated in some soils by iron concretions and manganese concretions. A manganese concretion with a root through the center has been found by Sherman and identified by him as pyrolusite (Sherman, et al., 1949). Manganese concretions develop near the surface under alternating wet and dry conditions.

Silicate clays are also believed to be in equilibrium with soil solution and may form from solution when the ionic concentrations are favorable (Garrels and Christ, 1965:359). The presence of potassium mica (an essential part of illite) in Hawaiian soils formed from rocks basically lacking in the mica structure, supports Garrels and Christ's hypothesis. Wentworth and his coworkers (1940) were the first to identify potassium mica in Hawaiian soils. Evidence indicates that it may form early in soil

genesis. Solutions from soils of the Kipapa transect seem presently to be unfavorable to illite synthesis or stability (Swindale and Uehara, 1965).

Illite has formed from basalt in other parts of the world. In India, a soil from augite basalt under low rainfall is calcium rich and montmorillonitic. Under about 80 inches of rainfall, the soils contained kaolin and illite clays with illite seemingly dominating the properties of the soil (Godse, 1958).

Rex (1965) has electron micrographs of illite laths radiating outward from kaolinite crystals in the same plane. This is evidence of the formation of illite from solution and not as a degradation product of a primary mineral.

Pedogenic trends with rainfall:

Tanada (1951) found several correlations of the chemistry of the surface of 19 Hawaiian and two Tahitian soils with rainfall. Log SiO_2/Al_2O_3, log SiO_2/Fe_2O_3, log SiO_2/TiO_2 and log percent kaolinite decreases linearly with the log of the mean annual rainfall. The respective slopes are -0.554, -1.204, -1.283, and -0.862 with correlations of -0.764, -0.905, -0.858, and -0.934. Chemical analyses of the colloidal fraction of each soil show that the greatest amount of silica is in the group of younger soils, of alumina is in the less than 40-inch rainfall group, and of iron and titanium is in the more than 75-inch rainfall group. Cation exchange capacities tend to be highest in the 40-75-inch

rainfall group.

Data of Tamura and co-workers (1953) show a decrease in percent kaolin with increasing rainfall and also a slight increase with depth. Saing's work (1964) agrees with Tamura. Saing suggested that the kaolin content of soils might converge at depth, probably in the saprolite.

The properties of water-holding capacity, moisture equivalent, clay content, cation-exchange capacity, and volume expansion is correlated with rainfall on soil derived from flood basalt of the Deccan Trap (Karale, 1958). In Hawaii, however, such correlations may not always exist due to the influence of ash.

METHODS

Sample preparation:

A sample splitter was used to separate about one-quarter of the field sample for air-drying. After air-drying, the samples were gently crushed in a mortar. Large roots, if any, were removed from the samples, but almost no inorganic materials were discarded.

Ten to 25 gram samples were prepared and fractioned according to Jackson's method (1965). Intensive cation removal was not followed since the solutions were not to be analyzed. The samples were acidified with pH 5 NaOAc buffer, treated with H_2O_2 (technical grade) for organic matter removal, deferrated with dithionite and sodium citrate, boiled for five minutes in 2 percent Na_2CO_3 to saturate the clays, and finally dispersed with distilled water. In the flocculating steps, about two or three times more NaCl was needed than called for in the method in order to obtain clear supernatants after centrifuging. The sands were separated using a 325 mesh sieve (43 microns) since a 50 micron sieve was not available. The silts, coarse clays, and fine clays were separated by centrifuging in an International Centrifuge Model UV at speeds calculated for an International Centrifuge Model 2.

Mineralogical analysis:

The sands were washed with H_2O_2 to remove any

remaining organic matter, then oven-dried, weighed, and examined under a petrographic microscope especially for signs of volcanic glass. Hydrogen peroxide treatment also seemed to remove clay from the sands. Part of the sand fractions (all in some cases) was ground to a silty texture and X-rayed with copper radiation. Five samples did not have enough sand for the X-ray technique used.

The silts were kept under water in storage until analyzed, then most of the water was evaporated on a warm plate (a few became drier than desired) followed by air-drying. The air-dry silts were transferred to Kodak film containers and weighed. They were made homogeneous in an agate mortar for X-raying, for differential thermal analyses, and for examination under the petrographic microscope. Copper radiation was used in spite of the high secondary iron radiation. An iron X-ray tube was used on several samples, but the results were similar to those of copper radiation.

One-tenth of each sample of coarse clay was pipetted into a previously weighed Kodak film container. After oven-drying at 110°C, they were tightly capped while hot, placed in a desiccator, and weighed within five minutes. The fine clays could not be weighed accurately due to their dilute suspensions (less than 5 parts per thousand) and rusting of cans during the evaporation of the water. Both fine and coarse clays were saturated with

magnesium and potassium for X-raying. Oriented potassium-saturated clays were X-rayed when dried at room temperature, at 350°C for two hours, and at 550°C for two hours. The magnesium-saturated clays were X-rayed before and after glycolation.

Differential thermal analysis of silts was done under ordinary laboratory conditions, but 100 mesh whole soil was heated with nitrogen gas passing through the sample to suppress the oxidation of organic matter. Stone's Controlled Environment System was used. A 0.1 gram sample was thoroughly mixed with 0.13 grams of calcined alumina and put in an atmosphere of 57 percent relative humidity for two days. Alumina was used to prevent caking, to make for more even heat conduction to the thermal couple, to make a porous medium which allows nitrogen gas to pass through more easily, and to prevent shrinkage away from the walls. Differential thermal analysis was used to measure the amount of gibbsite and kaolin, and as an indication of the type of kaolin clay.

Quartz was determined by X-ray diffraction (Cu-K_α radiation) and measuring the 3.35 angstrom peak.

The total illite content of each sample was determined by multiplying the total potassium oxide content by a factor of 7.2 determined for a Hawaiian illite by Juang (1965).

Free iron oxides are considered to be those extracted from 100 mesh oven-dry soil with dithionite at room temperature (Kilmer, 1960). A reduction in sample size due to the high percentage of free iron oxide in Hawaiian soils, was based on investigations by Watanabe (Hawaii, personal communication). The strength of the dichromate used was 0.0125 normal instead of the suggested 0.05 normal solution so that a larger volume could be used in the titration. One drop still gives a sharp end point.

Organic matter was determined on 20-mesh soil and on 100-mesh soil by oxidation with $K_2Cr_2O_7$ upon addition of concentrated H_2SO_4 (Walkley and Black, 1934).

Soil properties:

Fifteen-bar water was measured using a pressure membrane.

Cation-exchange capacity was determined by using neutral, normal NH_4OAc to saturate the exchange positions with the NH_4^+ ion. Potassium chloride was used to replace the NH_4^+ ion. The amount of replaced NH_4^+ ions was determined by making the solution basic with NaOH, distilling ammonia into boric acid, and titrating the boric acid with standard H_2SO_4.

Exchangeable calcium was precipitated with $Na_2C_2O_4$, washed, then titrated with 0.05 N $KMnO_4$.

Exchangeable magnesium was determined using a Perkins-Elmer Model 303 atomic absorption spectrophotometer.

Exchangeable sodium and potassium were determined by flame photometry on a Beckman DU.

Determination of the discriminant function:

The discriminant function uses the zirconium and nickel content of soils to determine whether the parent material is basaltic or andesitic in the present situation.

Total zirconium was measured by X-ray fluorescence using a LiF analyzer crystal and operating the tungsten tube at 40 kilovolts and 40 milliamps. Radiation from the tungsten tube was used as an internal standard against which the height of the zirconium peak was compared. One-fifth of the strontium K_β peak was subtracted from the zirconium peak as a correction for the strontium K_α peak under the zirconium peak. The zirconium peak is at 22.7° 2θ; the strontium K_β peak is at 26.8° 2θ; and the tungsten peak is at 31.8° 2θ. A rock standard, known as Hawaii Institute of Geophysics Standard-3, was mixed with 50 percent quartz and used as the standard for soils. Since tungsten was used as an internal standard, the difference between the soil matrix and the rock matrix may be reduced to some extent, although the author does not know to what extent. The soil was not oven-dried.

Nickel was determined by X-ray florescence using a LiF

analyzer crystal and operating the tungsten tube at 40 kilovolts and 35 milliamps. The peak at approximately 48.8° 2θ was run for a minute, then the background radiation at 50.2° 2θ was run for a minute or two. The rock standards used were W-1, quartz, HIGS-2, HIGS-6, and HIGS-8. Several soils were compared to these rock standards using the ratio of nickel peak height to background radiation (Andermann, 1958). The peak heights, alone, of these several soils were then used to form a standard curve to which the other soils were compared. The soils were air-dry.

Total chemical analyses of selected elements:

Approximately 0.4 gram (weighed exactly) of 100 mesh oven-dry soil was ignited, then dissolved in a solution containing HF, H_2SO_4, and H_2O. Most of the samples had a trace of material which would not dissolve.

Iron color was developed using mercaptoacetic acid, saturated sodium acetate buffer, and 2,2-bipyridine and absorbance was measured at 522 millimicrons on the Beckman DU.

Titanium-sulfate complex was developed using H_3PO_4, H_2SO_4 and H_2O_2. The absorbance was measured at 400 millimicrons on the Beckman DU.

Manganese was oxidized by periodate and the absorbance was measured at 545 millimicrons on the Beckman DU. Phosphoric acid eliminated interference by iron.

Calcium and magnesium were diluted 1:10 in a solution containing approximately 2000 ppm lanthanum to suppress aluminum interference in atomic absorption spectrophotometry (Williams, 1960). A single standard solution contained both calcium and magnesium in the range of 0 to 2 ppm and also contained 30 ppm of aluminum and 2000 ppm of lanthanum. A Perkins-Elmer Model 303 Atomic Absorption instrument was used.

Sodium and potassium were determined on a Beckman DU flame spectrophotometer.

DESCRIPTIONS OF SOIL SAMPLES

The approximate positions of the sample sites are shown in Figure 1. The elevation lines have been traced from a geological map prepared by Stearns and Macdonaid (1946). The isohyetal lines are a rough approximation of a map prepared by the U. S. Weather Bureau.

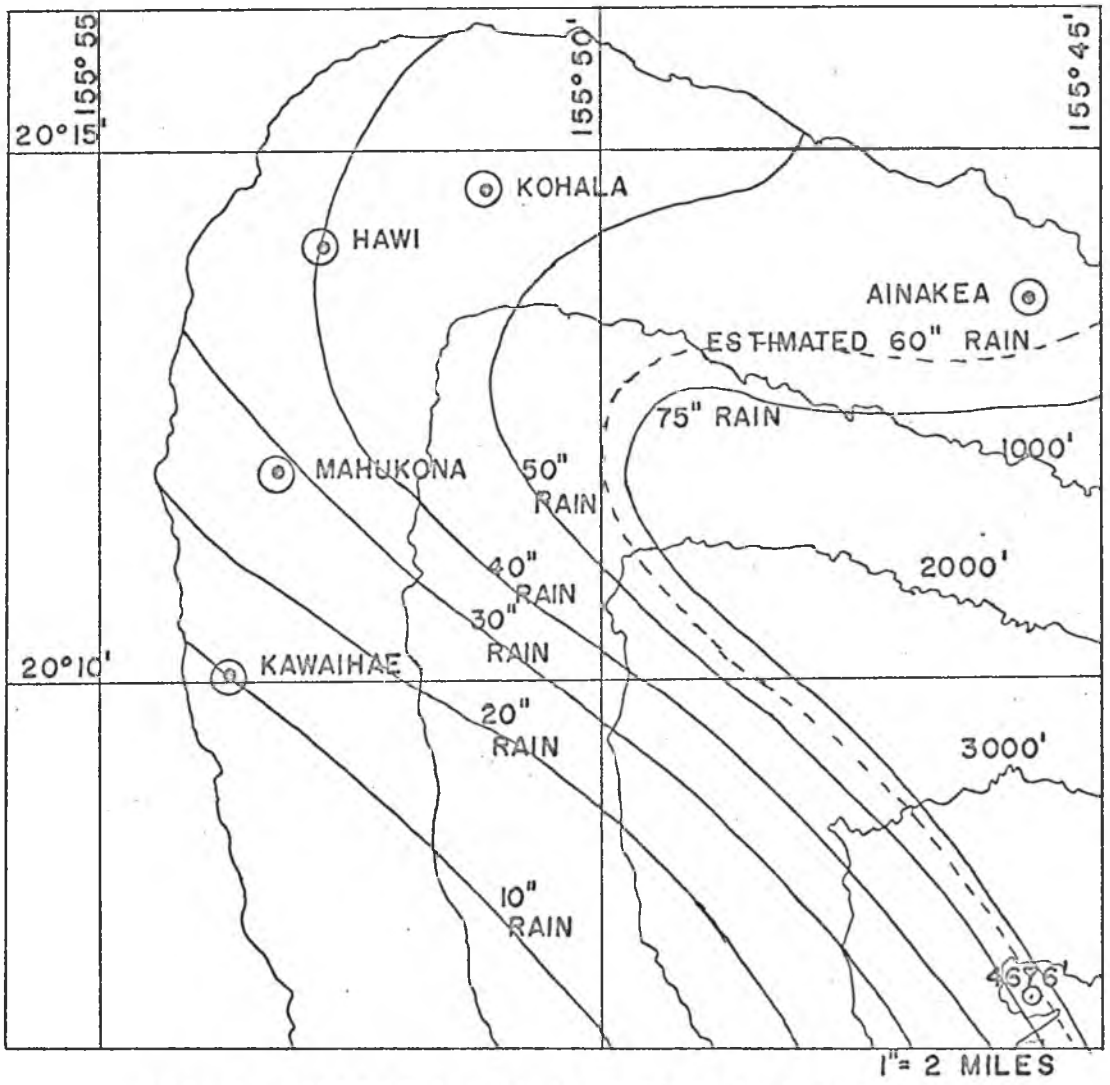


FIG. 1. ISOBARIC AND ISOHYETAL MAP SHOWING THE LOCATION OF EACH SAMPLE SITE

TABLE I. DESCRIPTION OF THE SAMPLE SITES (SWINDALE, University of Hawaii)

Soil series	Kawaihae	Mahukona	Hawi	Kohala	Ainakea
Great soil group	Red Desert	Low Humic Latosol	Low Humic Latosol	Low Humic Latosol	Humic Latosol
Location	155°53'37"W 20°10'02"N	155°53'14"W 20°12'01"N	155°52'48"W 20°14'07"N	155°51'11"W 20°14'44"N	155°45'46"W 20°13'25"N
Elevation	240 feet	420 feet	425 feet	570 feet	245 feet
Physiography	undulating west-facing slopes of Kohala Mt.	undulating west-facing slopes of Kohala Mt.	undulating easy-rolling north-west facing slope	easy-rolling north-facing slopes of Kohala Mt.	rolling north-facing slopes of Kohala Mt.
Slope at site	flat	3%	flat	nearly flat	2% to north
Relief	slightly convex microslope	convex microslope	slightly convex microrelief	small convex slope on general slope	convex microslope
Erosion	probable wind	wind	slight	?	?
Parent material	basalt or andesite (ash)	basalt or andesite	basalt	basalt or andesite	basalt or andesite (ash)
Stoniness	very stony	very stony surface	stones removed	none	none
Permeability	high	high	high	high	high
Drainage	well	well	well	well	well
Salt or alkali	none	none	none	none	none
Native vegetation or crop	keawe, swollen finger grass, pili-grass, ilima, ukaloa	swollen finger grass, ilima, ukaloa, some keawe	guinea grass, pasture	sugar cane	sugar cane
Climate	tropical semi-arid	tropical semi-arid	tropical sub-humid	tropical sub-humid	tropical
Annual rainfall	10 inches	27 inches	40 inches	45 inches	57 inches ?
Additional notes	strong wind		strong wind		strong wind, boulder at 17-36 inches

Soil profile descriptions:

The descriptions are by Swindale, University of Hawaii.

The colors were taken in the laboratory by the author and may not be too reliable.

KAWAIHAE

0- 5 cm: Dark reddish brown (5 YR 2/4, moist), brown (7.5 YR 4/6, dry); loam; weak, fine to medium subangular blocky structure and weak, medium platy structure; soft (dry), friable (moist), non-sticky and non-plastic (wet); smooth abrupt boundary; common roots; many fine pores; common, fine partially weathered rock fragments.

5- 20 cm: Dark reddish brown (5 YR 2/4, moist), brown (7.5 YR 4/6, dry); sandy loam; weak, fine prismatic structure; slightly hard (dry), friable to firm (moist), non-sticky and non-plastic (wet); smooth, clear boundary; common roots; many fine pores; common, fine to coarse partially weathered rock fragments.

20- 40 cm: Dark brown (7.5 YR 3/4, moist), gray yellowish brown (10 YR 4/3, dry); loam; weak, fine to coarse subangular blocky structure; soft (dry), friable (moist), non-sticky and non-plastic (wet); smooth clear boundary; common roots; abundant

fine pores; common, fine to coarse partially weathered rock fragments.

40- 60 cm: Dark brown (7.5 YR 3/4, moist), gray yellowish brown (10 YR 5/3, dry); silt loam; structureless; soft (dry), friable (moist), non-sticky and non-plastic (wet); smooth abrupt boundary; few roots; many pores; many partially weathered rock fragments; fine calcium carbonate.

60 cm on: Partially weathered igneous rock.

MAHUKONA

0- 6 cm: Dark reddish brown (5 YR 2/4, moist), brown (7.5 YR 4/6, dry); silty clay loam; weak, fine subangular blocky structure; soft (dry), friable (moist), non-sticky and plastic (wet); wavy clear boundary; common roots; few fine pores.

6- 31 cm: Dark reddish brown (5 YR 2/4, moist), brown (7.5 YR 4/6, dry); silty clay loam; weak, medium prismatic structure; slightly hard (dry), friable to firm (moist), non-sticky and plastic (wet); smooth gradual boundary; common roots; abundant fine pores; few rock fragments.

31- 41 cm: Dark reddish brown (5 YR 2/4, moist), brown (7.5 YR 4/4, dry); clay loam; moderate, fine to medium subangular blocky structure; hard (dry),

firm (moist), slightly sticky and plastic (wet); wavy clear boundary; few roots; abundant fine pores; common rock fragments.

41- 75 cm: Dark reddish brown (5 YR 2/3, moist), dark brown (7.5 YR 3/4, dry); clay; strong, fine to medium subangular blocky structure; hard (dry), firm (moist), sticky and plastic (wet); diffuse boundary; few roots; common fine pores; abundant rock fragments.

75 cm on: Dark reddish brown (5 YR 2/3, moist), dark brown (7.5 YR 3/4, dry); clay; strong, fine to medium subangular blocky structure and granular structure; hard (dry), friable to firm (moist), sticky and plastic (wet).

HAWI

0- 15 cm: Dark brown (7.5 YR 3/3, moist), dark brown (10 YR 3/4, dry); clay; strong fine granular structure; soft (dry), friable (moist), sticky and plastic (wet); smooth clear boundary; abundant roots; fine and very fine pores; few rock fragments and a few black specks.

15- 38 cm: Dark brown (7.5 YR 3/3, moist), dark brown (10 YR 3/4, dry); clay; moderate, coarse blocky structure and moderate, fine subangular blocky

structure; soft but ped hard (dry), friable (moist), sticky and plastic (wet); wavy clear boundary; abundant roots; fine to very fine pores; few black specks.

38- 66 cm: Dark brown (7.5 YR 3/3, moist), dark brown (10 YR 3/4, dry); clay loam; weak, coarse prismatic structure; hard (dry), very firm (moist), sticky and plastic (wet), wavy gradual boundary; few roots confined to vertical abundant fine cracks; few rock fragments.

66- 83 cm: Dark brown (7.5 YR 3/4, moist), dark brown (10 YR 3/4, dry); silty clay loam; weak, medium subangular blocky structure; hard (dry), firm (moist), sticky and plastic (wet); wavy gradual boundary; few roots, abundant fine to very fine pores; common rock fragments.

83-122 cm: Dark brown (7.5 YR 3/4, moist), dark brown (10 YR 3/4, dry); silty clay loam; structureless; soft (dry), friable to firm (moist), slightly sticky and plastic (wet); wavy gradual boundary; very few roots; abundant fine to very fine pores; many rock fragments.

122 cm on: Dark brown (7.5 YR 3/4, moist), dark brown (10 YR 3/4, dry); silt loam; weak, medium

subangular blocky structure; soft (dry), friable (moist), slightly sticky and slightly plastic (wet); wavy gradual boundary; very few roots; abundant fine to very fine pores.

KOHALA

0- 15 cm: Dark brown (7.5 YR 3/3, moist), dark brown (10 YR 3/4, dry); clay; moderate, fine to very fine subangular blocky structure; loose (dry), friable (moist), sticky and plastic (wet); smooth gradual boundary; few roots; many very fine pores; few black specks.

15- 43 cm: Dark brown (7.5 YR 3/3, moist), brown (10 YR 4/4, dry); sandy clay loam; weak, fine to very fine subangular blocky structure; soft (dry), friable (moist), sticky and plastic (wet); smooth gradual boundary; few roots; many fine pores; few weathered rock fragments; common cutans on ped faces.

43- 66 cm: Dark brown (7.5 YR 3/3, moist), brown (10 YR 4/4, dry); sandy clay loam; moderate, fine subangular blocky structure; loose (dry), friable (moist), sticky and plastic (wet); wavy gradual boundary; few roots; many fine pores; few rock fragments.

66- 91 cm: Dark brown (7.5 YR 3/3, moist) brown (10 YR 4/4, dry); gritty sandy loam; moderate, fine to very fine subangular blocky structure; soft (dry), friable to firm (moist), slightly sticky and slightly plastic (wet); smooth clear boundary; few roots; many fine pores; many rock fragments; numerous cutans on ped faces.

91-148 cm: Dark brown (7.5 YR 3/3, moist), brown (10 YR 4/6, dry); sandy loam; weathered rock fragments with some pedological organization between them.

AINAKEA

0- 20 cm: Dark brown (7.5 YR 3/3, moist), grayish yellow brown (10 YR 5/4, dry); silty clay loam; moderate to strong, fine subangular blocky structure; soft (dry), friable to firm (moist), slightly sticky and plastic (wet); smooth gradual boundary; few roots; many very fine interstitial pores; few rocks and dark red specks.

20- 43 cm: Dark brown (7.5 YR 3/3, moist), grayish yellow brown (10 YR 5/4, dry); silty clay loam; strong, fine granular and subangular blocky structure and weak, coarse granular structure; soft (dry), friable (moist), slightly sticky and plastic, smooth abrupt boundary; few roots; many very fine inter-

stitial pores; few rocks and dark red specks.

43- 61 cm: Dark brown (10 YR 3/3, moist), grayish yellow brown (10 YR 5/4, dry); silty clay loam; moderate, fine to medium subangular blocky structure; soft (dry), friable (moist), non-sticky and plastic (wet); smooth gradual boundary; few roots; common fine pores; shiny, discontinuous stress cutans.

61- 79 cm: Dark brown (10 YR 3/3, moist), yellowish brown (10 YR 5/6, dry); silty clay loam; strong, fine to medium subangular blocky structure; soft (dry), friable (moist), non-sticky and plastic (wet); smooth gradual boundary; few roots; common large pores; shiny, continuous stress cutans.

79- 99 cm: Dark brown (10 YR 3/4, moist), yellowish brown (10 YR 5/6, dry); silty clay loam; strong, fine to medium subangular blocky structure; soft (dry), friable (moist), non-sticky and plastic (wet); smooth gradual boundary; very few roots; large pores; shiny continuous stress cutans and patchy illuviation cutans.

99- 147 cm: Brown (7.5 YR 4/6, moist), bright brown (7.5 YR 5/6, dry); silt loam; strong, medium subangular blocky structure; slightly hard (dry), firm (moist), non-sticky and slightly plastic (wet); smooth gradual

boundary; very few roots; abundant partly weathered rocks. Soil forms a matrix between the soft weathered rocks.

147 cm on: Dark brown (7.5 YR 3/4, moist), brown (10 YR 4/4, dry); silt loam; soil forms a matrix between the soft weathered rocks.

RESULTS AND DISCUSSION

Composition and Parent Rock

General composition and selected properties:

Figure 2 shows the change in composition and a few properties with depth in each soil. The soils are arranged according to increasing rainfall so that the reader may see the trends with rainfall.

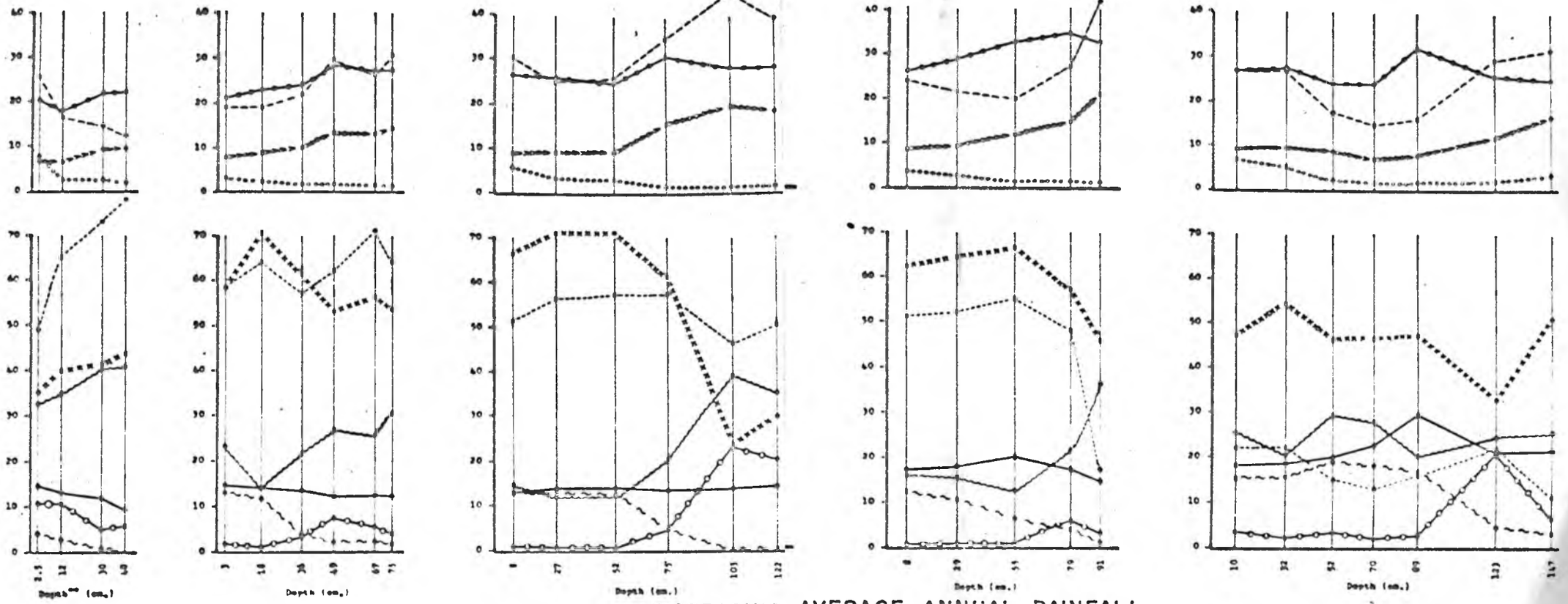
The amount of clay is determined indirectly by subtraction. Clay is calculated in this manner because of the inaccuracy of weighing fine clays directly. The suspensions of fine clays were very dilute, less than 5 parts per 1000. Mechanical loss during the separation procedure is negligible, but the chemical loss from the sand and silt fractions by boiling in Na_2CO_3, although unknown, may be significant. The chemical loss from silt and sand would give an apparent increase in the amount of clay when the calculation is by difference.

In Figure 2, the vertical lines represent the middle of the horizons. The lowest horizon is represented by its upper boundary.

The trends in Figure 2 are partly dependent on parent rock. A discontinuity in the parent rock could result in a discontinuity in trends within each profile and between profiles.

Parent rock:

The discriminant function which Kendall (cited in Kimura,



INCREASING AVERAGE ANNUAL RAINFALL

10 INCHES	27 INCHES	40 INCHES	45 INCHES	57 INCHES
KAWAIHAE	MAHUKONA	HAWI	KOHALA	AINAKEA

Fig. 2. Changes in composition and in selected properties with depth of each of the five soil profiles arrayed according to rainfall. Line and symbol identification:

- 15 bar water
- Cation exchange capacity
- Water in air dry soil
- Organic matter
- Kaolin
- Clay (less than 2.0 microns)
- Silt (2.0 to 43 microns)
- Free iron oxides
- Sand (43 microns to 2 millimeters)
- Illite

Cation exchange capacity is in milliequivalents per 100 grams of oven dry soil.
Depth to middle of horizons and to top of deepest horizon.

1966) explains, has been solved for Low Humic Latosols derived from basalt and andesite. The discriminant function, solved by Kimura, equals zirconium minus 1.44 nickel.

The separation between the five soils is sharp (Fig. 3). The Kawaihae sample appears to have formed from basaltic rock which would probably be of the Pololu volcanic series. Cline (1954:469) states that the Kawaihae soil series is from alluvium and volcanic ash. Since volcanic ash weathers differently from basalt or andesite, we cannot be certain of the results. If this Kawaihae sample is from ash, the ash most likely had only a small amount of glass in view of the high kaolin percentage (Fig. 2 and Table III) in the soil. Glass should yield a higher amorphous component than could be present in the sample of Kawaihae soil. In Hawaii, ash should be largely glass and any abundant ash should be "andesitic" (Macdonald, University of Hawaii, personal communication).

The results are probably valid for the Mahukona, Hawi, and Kohala soils since there is little doubt that they are formed from either basalt or andesite. The Mahukona soil may be derived from the same andesite found near the town of Mahukona. That andesite is classified by Stearns (1946:171) as part of the Pololu volcanic series. This is important, in view of Stearns' statement (Stearns and Macdonald, 1946:179) that soils derived from the Hawi volcanic series are shallower than those from the Pololu

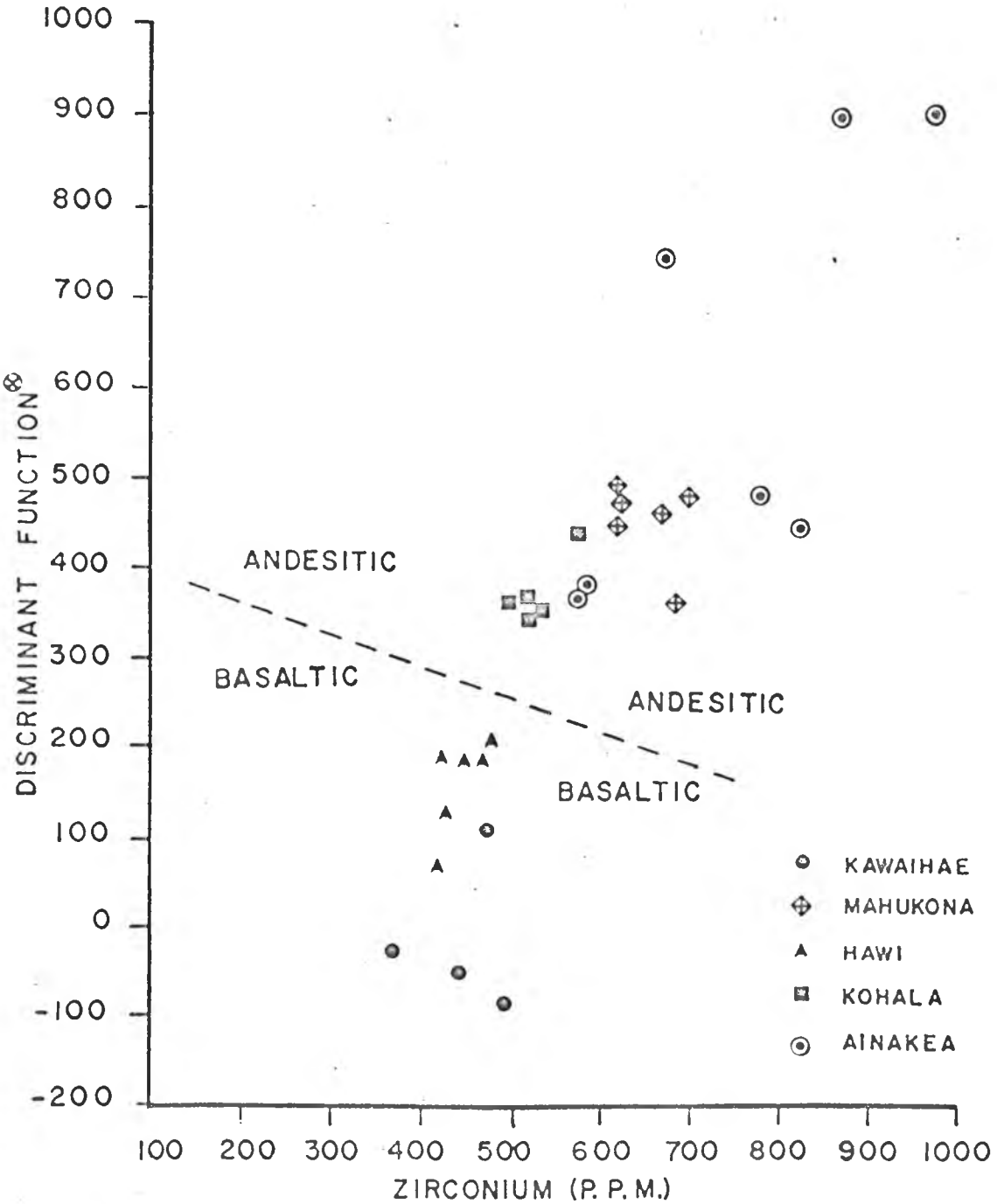


FIG. 3. SEPARATION OF THE SOIL HORIZONS ACCORDING TO THE ANDESITIC OR BASALTIC NATURE OF THE PARENT ROCKS

⊗ $D.F. = Zr - 1.44\ Ni$

TABLE II. DISCRIMINANT FUNCTION DATA

Soil Series	Depth (cm)	Zr* PPM	Ni** PPM	1.44 Ni	Discriminant Function Zr--1.44 Ni	Rock
Kawaihae	0- 5	470	250	360	110	Basaltic
	5- 20	490	400	575	- 85	"
	20- 40	440	340	490	- 50	"
	40- 60	365	270	390	- 25	"
Mahukona	0- 6	680	150	215	365	Andesitic
	6- 31	695	145	210	485	"
	31- 41	665	140	200	465	"
	41- 60	620	100	145	475	"
	60- 75	615	115	165	450	"
	75+	615	85	120	495	"
Hawi	0- 15	445	180	260	185	Basaltic
	15- 38	465	195	280	185	"
	38- 66	475	185	265	210	"
	66- 84	420	160	230	190	"
	84-122	425	205	295	130	"
	122+	415	235	340	70	"
Kohala	0- 15	530	120	175	355	Andesitic
	15- 43	515	120	175	345	"
	43- 66	570	90	130	440	"
	66- 99	515	100	145	370	"
	99-122	495	90	130	365	"
Ainakea	0- 20	580	135	195	385	Andesitic
	20- 43	570	140	200	370	"
	43- 61	750	60	85	665	"
	61- 79	910	35	50	860	"
	79- 99	965	35	50	915	"
	99-147	820	255	370	450	"
	147+	775	200	290	485	"

* By X-raying air dry soil and comparing to a rock standard using the tungsten peak as an internal standard.

**By X-raying air dry soil and comparing to several rock standards using scattered radiation as an internal standard.

volcanic series. The trend of increasing depth of the three drier soils which most likely are in the Pololu volcanic series is interrupted by the comparatively shallow Kohala soil which is probably from the Hawi volcanic series. The Ainakea soil, also probably derived from the Hawi volcanic series, may be shallower than if it had been derived from the Pololu volcanic series. The alternative idea to explain the shallowness of the Kohala soil relative to the Hawi soil is truncation of the Kohala soil sampling site as will be explained in the section on illite.

Secondary Minerals vs. Rainfall

General statement:

There can be but little doubt that free iron oxides, kaolin, illite, quartz, and gibbsite are definitely related to rainfall, at least between 10 and 60 inches per year (Figs. 4, 5, 6 and Table III). The increase in secondary minerals, such as illite and quartz, with an increase in rainfall could be due to either a greater degree of formation with respect to a given amount of parent rock and/or it could be due to a constant amount being formed from a given amount of parent rock which then becomes concentrated as certain other elements are lost. Both of these principles are apparent in the free iron oxide and total iron content of the soils. Iron comprises a fairly constant percentage of parent rock, generally 11 to 14.5 percent Fe_2O_3 in andesites and basalts

of the Kohala Mountain according to Washington's analyses (Stearns and Macdonald, 1946:87), a large increase in total iron in soil should be due to its being concentrated.

Total iron, resistant iron, and free iron:

Within a soil profile, total iron is fairly constant with depth. The mechanism which concentrates the iron acts very early in the process of rock weathering since the concentration of iron in the saprolitic horizon is almost the same as in the surface horizon of each soil (Table III). The loss of silica from the alteration of plagioclase, which appears to be fairly complete even in the saprolitic soil, and the loss of most of the MgO, CaO, and Na_2O (Table IV) can account for the concentration of iron in soils being approximately twice its concentration in the parent rock. If the end products of rock weathering which form soil in the saprolitic horizons are fairly stable, further concentration of iron should not be very great.

Figure 4 may indicate to some people that an increase in rainfall favors the formation of free iron oxides. This may be true in many cases, but in the sequence of soils around the Kohala Mountain, it is more likely a reflection of the concentration of total iron discussed above.

In Table V, total iron (given on an oven-dry, organic-matter-free basis in Table III) has been normalized to 25.0 percent of the soil which is about twice the concentration of iron in the

TABLE III. IRON, TITANIUM, AND SECONDARY MINERALS*

Soil Series	Depth (cm)	Total Fe_2O_3	Free Fe_2O_3	Resistant Fe_2O_3	Titanium	Kaolin	Quartz	Illite	Gibbsite
Kawaihae	0- 5	25.0	15.3	9.7	5.74	53	0.9	3.8	5.9
	5- 20	24.6	13.0	11.6	5.08	66	0.8	2.5	4.4
	20- 40	23.7	11.7	12.0	5.17	75	0.5	0.7	3.6
	40- 60	24.4	9.0	15.4	5.22	79	0.0	0.0	2.7
Mahukona	0- 6	21.6	14.6	7.0	4.77	60	2.4	13.3	1.4
	6- 31	21.4	13.8	7.6	4.75	65	2.2	11.8	1.4
	31- 41	21.5	13.2	8.3	4.57	57	1.6	3.8	0.5
	41- 60	20.6	11.9	8.7	4.92	63	0.8	2.0	0.3
	60- 75	21.8	12.2	9.6	5.50	71	0.8	1.9	0.3
	75+	23.2	11.8	11.4	5.07	64	0.5	1.4	trace
Hawi	0- 15	19.7	13.4	6.3	4.10	54	5.3	13.4	2.6
	15- 38	19.3	13.9	5.4	3.99	58	4.9	13.0	2.2
	38- 66	19.9	13.8	6.1	4.29	59	4.9	13.0	2.2
	66- 84	19.7	13.1	6.6	4.12	58	2.1	4.6	1.4
	84-122	22.9	13.5	9.4	5.23	46	1.3	0.3	0.5
	122+	21.7	14.1	7.6	4.98	50	0.5	0.5	0.3
Kohala	0- 15	25.0	17.3	7.7	5.35	53	3.8	12.7	5.7
	15- 43	25.7	17.6	8.1	5.34	53	4.2	10.7	5.8
	43- 66	25.6	19.4	6.2	5.05	56	2.2	6.3	8.2
	66- 99	23.1	16.8	6.3	5.00	49	1.4	5.9	14.2
	99-122	23.8	14.3	9.5	4.70	17	0.9	1.1	14.4
Ainakea	0- 20	28.5	18.9	9.6	8.35	23	9.1	16.3	6.4
	20- 43	28.8	19.1	9.7	8.32	23	8.6	16.4	6.8
	43- 61	32.7	19.8	12.9	12.7	16	5.7	19.3	6.6
	61- 79	35.0	22.5	12.5	14.0	14	6.2	18.5	7.4
	79- 99	38.7	29.1	9.6	14.0	16	3.1	16.8	8.5
	99-147	31.5	21.0	10.5	8.80	23	1.1	4.6	10.2
	147+	32.2	21.5	10.7	6.94	12	0.4	3.3	14.0

*Percent of oven-dry, organic-matter-free soil.

TABLE IV. TOTAL AMOUNT OF SELECTED ELEMENTS IN THE SOILS

Soil Series	Depth (cm)	MnO %	CaO %	MgO %	K_2O %	Na_2O %
Kawaihae	0- 5	0.31	0.57	1.41	0.32	0.19
	20- 40	0.18	0.16	1.31	0.13	0.14
	40- 60	0.14	0.16	1.69	0.30	0.14
Mahukona	0- 6	0.50	0.22	1.06	1.01	0.24
	41- 60	0.21	0.54	1.50	0.28	0.51
Hawi	0- 15	0.45	0.66	1.07	1.08	0.23
	38- 66	0.42	0.38	1.04	0.99	0.25
	84-122	0.16	1.02	2.32	0.37	0.44
Kohala	0- 15	0.69	0.29	0.84	0.98	0.16
Ainakea	0- 20	0.38	0.25	1.10	1.14	0.19
	79- 99	0.12	0.17	0.68	1.19	0.13
	99-147	0.15	0.16	0.61	0.33	0.12

original rock. Normalization of total iron should remove most of the effect of different degrees of concentration so that the effect of rainfall in the formation of free iron oxides may be more clearly seen. With reference to Table V, the following points should be noticed:

1. Assuming that parent rock is fairly constant within the Hawi and Kohala soils (Fig. 3 and Table II) and that weathering should be more severe in the surface horizon than in the lower horizons, it appears that the resistant iron minerals are not being converted to free iron oxides in these soils. If the resistant iron minerals were being converted to free iron oxides, the amount of the latter should be greater in the surface horizons when eluviation is not present.
2. In view of point 1, the increase of resistant (unweathered) iron minerals with depth in the Kawaihae soil (10 inches of rainfall) and to a lesser extent in the Mahukona soil (27 inches of rainfall), indicate that free iron oxides may still be forming in these soils.
3. The discriminant functions of the surface horizons of the Mahukona, Kohala, and Ainakea soils are very similar (365, 355, and 385, respectively), indicating similar parent rocks. The evenness of resistant iron minerals (8.1, 7.7, and 7.4 percent, respectively) may mean that

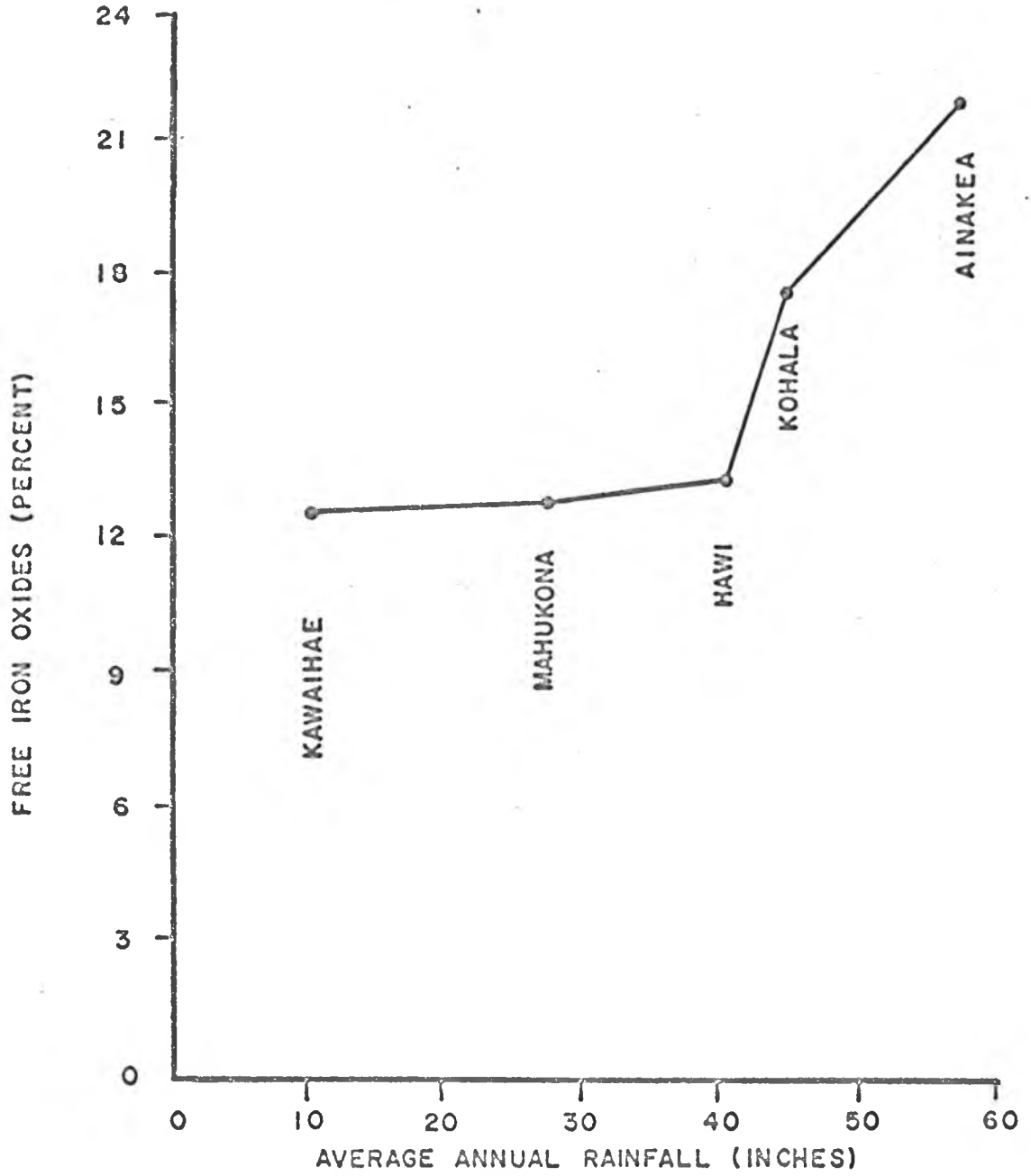


FIG. 4. WEIGHTED AVERAGE PERCENT OF FREE IRON OXIDES IN FIVE PROFILES AS A FUNCTION OF RAINFALL

the effect of rainfall under the given condition is slight or nil on the conversion of resistant iron to free iron oxides. This must be stated with the reservation that similar discriminant functions do not necessarily mean that the parent rocks had the same amount of resistant iron minerals. Point 1 is within the same profile where the parent rocks are likely to be the same rock.

4. Table VI indicates that the formation of free iron oxides in the lowest horizons of the Hawi and Ainakea soils is almost complete to the point where only the resistant iron minerals remain. Weathering of iron-bearing minerals is still occurring in the other three soils in the deepest horizon.

The use of free iron oxides as an indication of the degree of weathering of a soil does not necessarily indicate the amount of free iron being released from the parent rocks. Their concentration also indicates the weathering of other constituents of the parent rock. In the weathering process, the loss of silica from feldspars during the formation of kaolin is very important. The decrease in amount of kaolin (Fig. 5) shows an inverse relationship to free iron oxides (Fig. 4), and may be a more direct measure of weathering.

Kaolins:

From 40 to 57 inches of rainfall, free iron oxides increase

Table V. Constituents in the Upper 40 Centimeters Adjusted to a Constant Concentration of Total Iron

Soil Series	Depth (cm)	Total Iron Fe_2O_3	Free Iron Fe_2O_3	Resistant Iron Fe_2O_3	TiO_2	Illite	Quartz
Kawaihae	0- 5	25.0	15.3	9.7	5.74	3.8	0.9
	5-20	25.0	13.4	11.6	5.16	2.5	0.8
	20-40	25.0	13.0	12.0	5.45	0.7	0.5
Mahukona	0- 6	25.0	16.9	8.1	5.52	15.4	2.8
	6-31	25.0	16.1	8.9	5.55	13.8	2.6
	31-41	25.0	15.3	9.7	5.32	4.4	1.9
Hawi	0-15	25.0	17.0	8.0	5.20	17.0	6.7
	15-38	25.0	18.0	7.0	5.16	16.8	6.4
Kohala	0-15	25.0	17.3	7.7	5.35	12.7	3.8
	15-43	25.0	17.6	7.4	5.20	10.4	4.1
Ainakea	0-20	25.0	17.6*	7.4	6.58	14.3	7.2
	20-43	25.0	17.4	7.6	6.55	14.2	6.8

*Adjusted to compensate for eluviation of free iron oxides by averaging.

Table VI. Constituents in the Saprolitic Horizons Adjusted to a Constant Concentration of Total Iron

Soil Series	Depth (cm)	Total Iron Fe_2O_3	Free Iron Fe_2O_3	Resistant Iron Fe_2O_3	TiO_2	Illite	Quartz
Kawaihae	40-60	25.0	9.2	15.8	5.35	0.0	0.0
Mahukona	75+	25.0	12.7	12.3	5.47	1.5	0.5
Hawi	122+	25.0	16.2	8.8	5.74	0.6	0.6
Kohala	99-122	25.0	15.0	10.0	4.94	1.1	0.9
Ainakea	147+	25.0	16.7	8.3	5.39	1.3	0.3

by about two-thirds (Fig. 4) while kaolins decrease by almost two-thirds (Fig. 5). The trend of kaolin to decrease with increasing rainfall is very apparent even in a comparison of only the saprolitic horizons. Quite possibly, when the rainfall is greater than 40 inches, a portion of the feldspars or other materials, such as glass, may convert directly to gibbsite without going through the kaolin stage of weathering at all or for only a very brief period. The trend of decrease in kaolins with increase in rainfall agrees with the results of other workers in Hawaii mentioned in the literature review.

The kaolin content is less in the surfaces than at a depth of 50 to 60 centimeters (Fig. 2). Possibly, a combination of rainfall and higher temperatures at the surface is the cause. Conditions in the surfaces affect kaolins, as X-ray examinations indicate (Figs. 6-11).

A combination of X-ray and differential thermal analysis indicates that the clays are mostly halloysite (Figs. 6-12). Examinations of oriented fine clays from the lower horizons do not show a 7.2 angstrom peak when air dry but do show a strong one when dried at 350°C for two hours. Differential thermal analysis of the whole soil of each horizon indicates that kaolins in the surface horizons are very similar to those in the lower horizons (Fig. 12). The shape and low temperature (490°C to 515°C) of the endothermic peak remain fairly constant among the

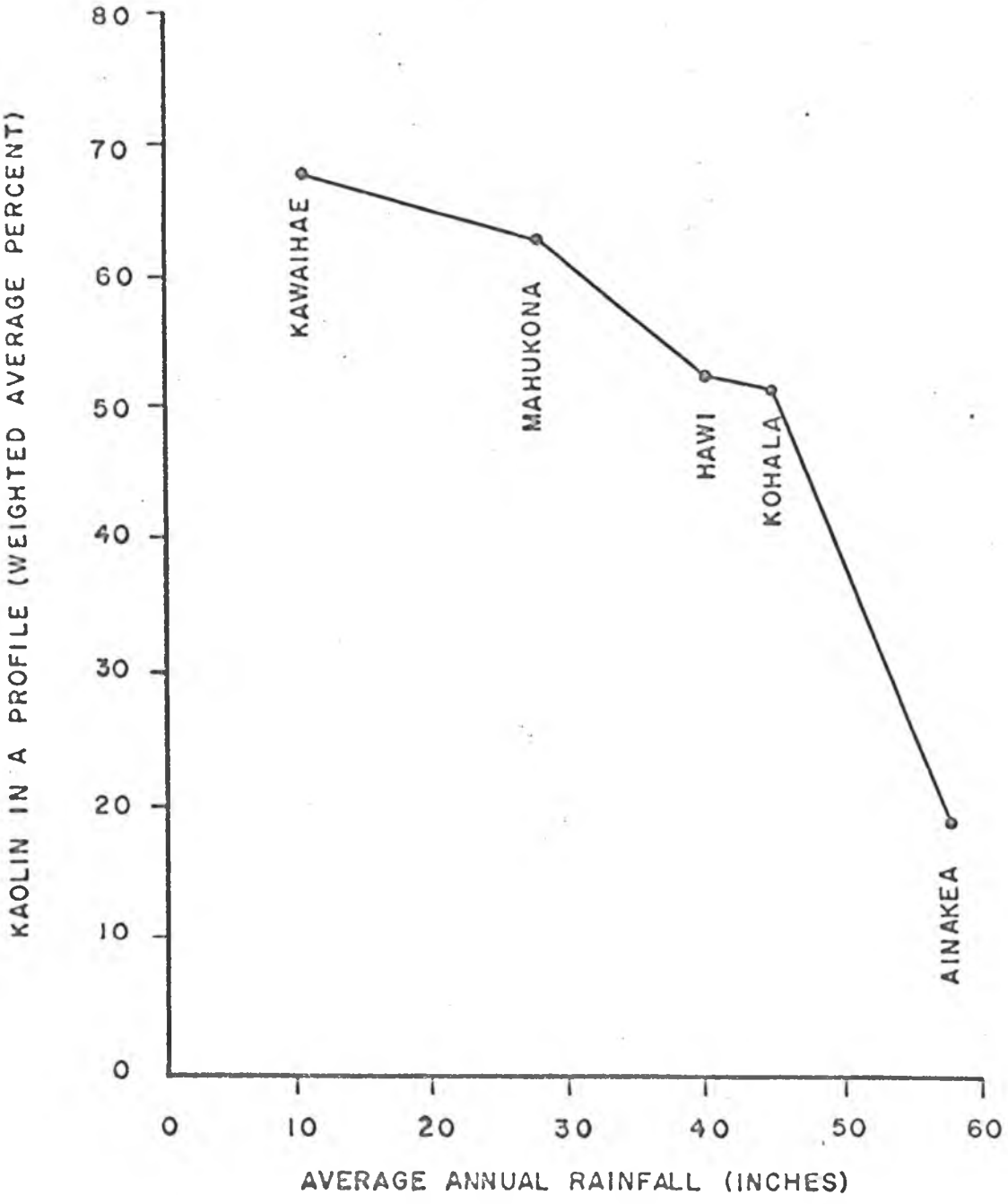


FIG. 5. DECREASE IN KAOLIN AS A FUNCTION OF RAINFALL

various horizons, more constant within a single profile than between the profiles. Dehydration near the surface is probably due to heat from the sunlight. Hydration gradually increases with depth. A greater degree of hydration of fine clays in the surface horizons of the Kohala and Ainakea soils compared to the drier soils may be due to shade from more clouds and denser vegetation which could be expected in higher rainfall zones.

The idea that the kaolins are mostly halloysite is based solely on the change of the 10 angstrom peak to approximately 7.2 angstroms upon heating to 350°C for two hours and on the similarities of the differential thermal analyses patterns. The halloysite is different from the standard halloysite from Bedford, Indiana. In the fourth horizon of the Kawaihae soil (Table III) based on oven dry, organic matter-free soil, the sum total of iron, titanium, gibbsite, and kaolin which is based on the halloysite standard differential thermal analysis curve equals 110 percent. When kaolin is based on standard kaolinite from Lewiston, Montana, the sum equals 96 percent which is a much more acceptable result. This may be the result of different heat conductances of the soil-alumina mixture which under-filled the sample holder and the standard clay-alumina mixture which completely filled the sample holder. It may, however, be due to a crystalline structure which approaches that of kaolinite. The very low intensity of the 020 peak (4.42 angstroms), absent or almost absent in many

cases, apparently is not typical of halloysite. Brown (1961:88) states:

> The 02 band diffracted by halloysite greatly increases the intensity in the 4.4 Å region as compared with the intensity of the 001 reflection. Usually, for kaolinite, sufficient orientation is present to make the intensity of the 001 line at least twice that of the 020 and 11l lines near d=4.4 Å. If these intensities are more nearly equal than the ratio 2:1, then the possibility of halloysite must be considered.

In a very general summary the kaolin clays of this sequence of soils range from dehydrated to hydrated halloysite, are less than a half circle in cross section, and have a stronger crystallinity than a standard halloysite.

In the silt fractions, especially of the drier soils, there is a large amount of kaolin. The silt in the lowest horizon of the Kawaihae soil is over 50 percent kaolin, yet it gives only a hint of a peak in a powder pattern (Fig. 13). If the kaolin particles were of silt size, they would tend to become oriented and give peaks at least as good as those of a small concentration of gibbsite. Under the petrographic microscope, including the use of reflected light, neither clay particles nor aggregates of clay were seen. The non-opaque particles appeared to be like altered volcanic glass which never went to extinction under crossed nicols. Kaolins may be altered microliths of feldspar within an altered glass matrix. The possibility that they are individual kaolin particles which have become tightly cemented together, espcially in the drier soils, cannot be

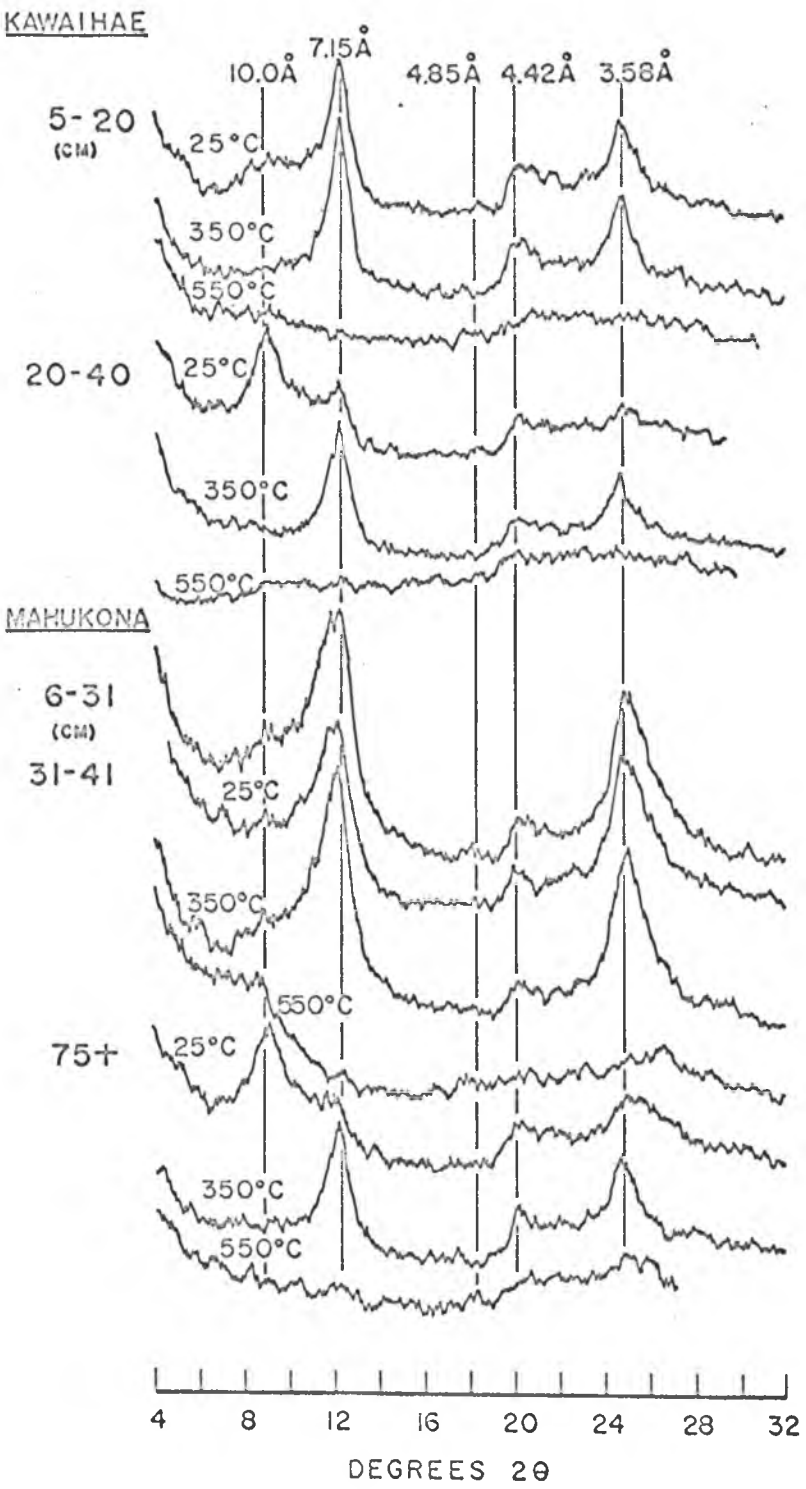


FIG. 6. X-RAY PATTERNS OF POTASSIUM-SATURATED FINE CLAYS OF THE KAWAIHAE AND MAHUKONA SOILS

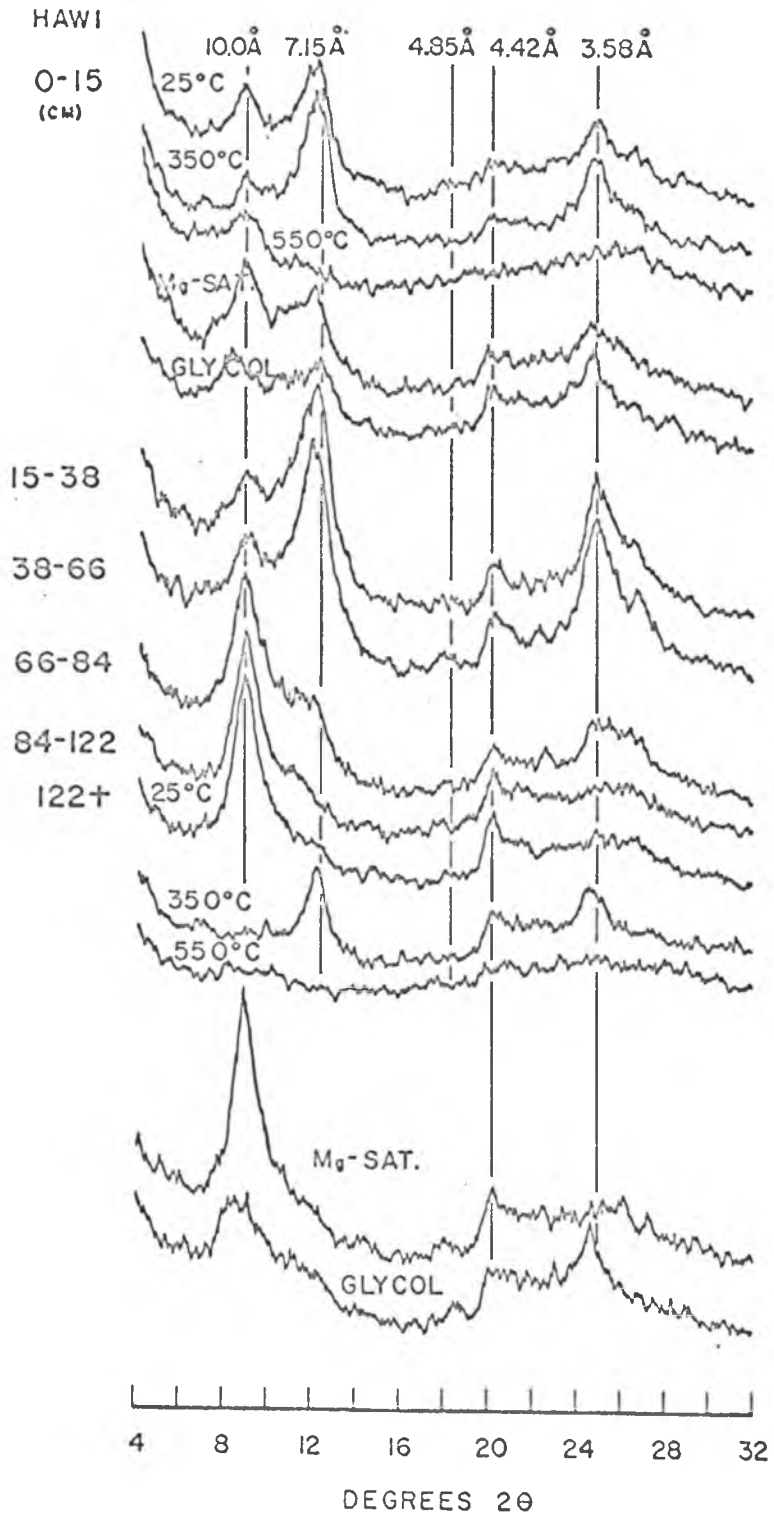


FIG. 7. X-RAY PATTERNS OF POTASSIUM-SATURATED FINE CLAY OF THE HAWI SOIL

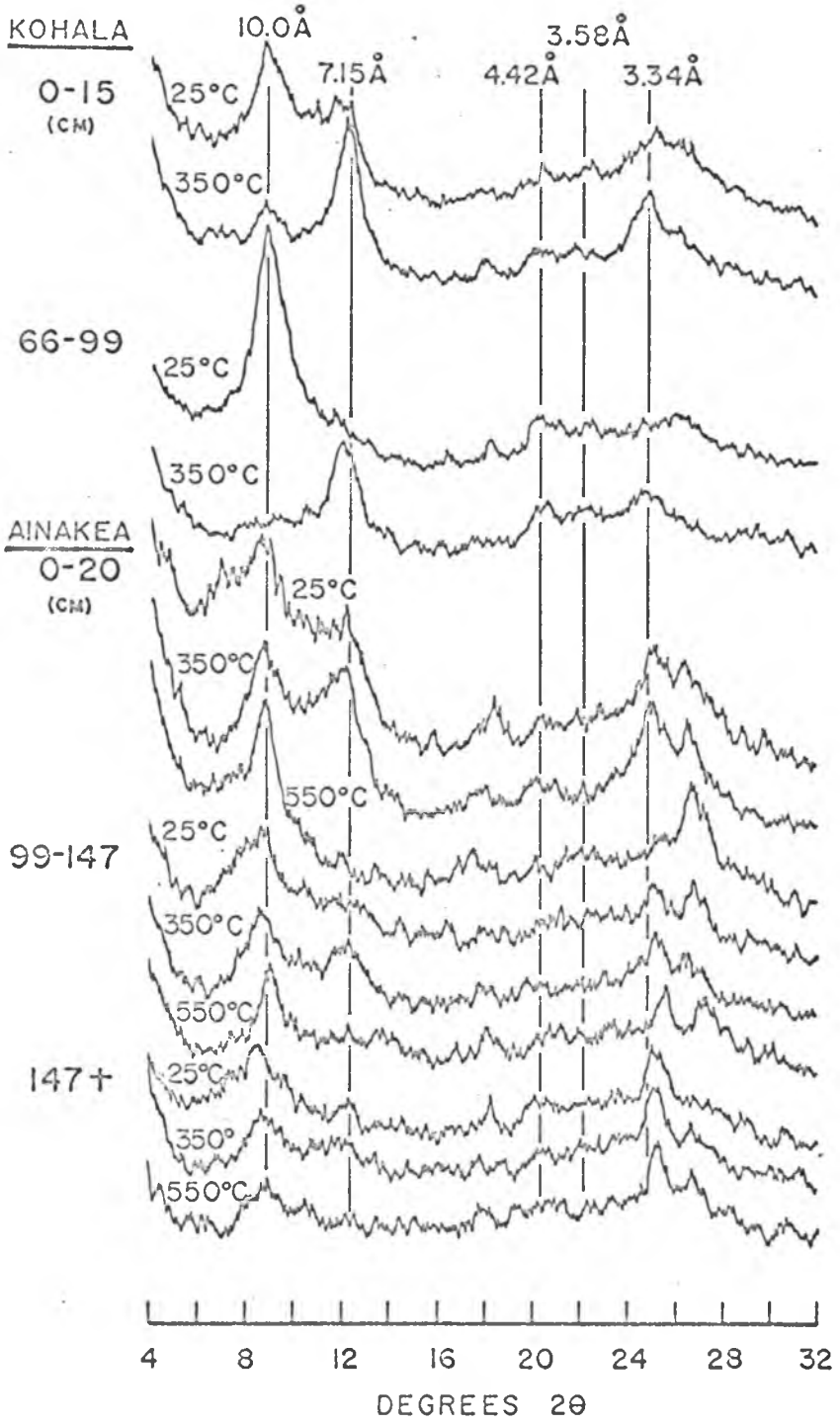


FIG. 8. X-RAY PATTERNS OF POTASSIUM-SATURATED FINE CLAYS OF THE KOHALA AND AINAKEA SOILS

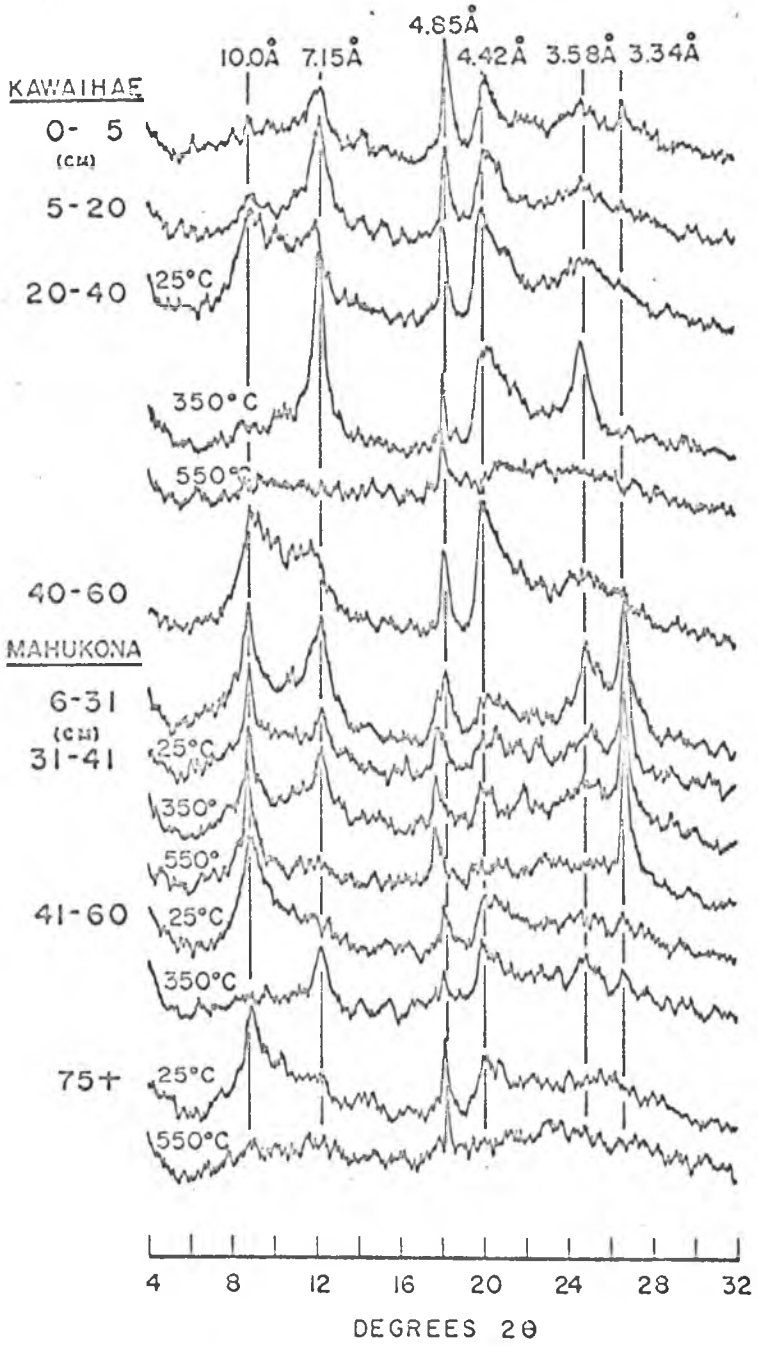


FIG. 9. X-RAY PATTERNS OF POTASSIUM-SATURATED COARSE CLAYS OF THE KAWAIHAE AND MAHUKONA SOILS

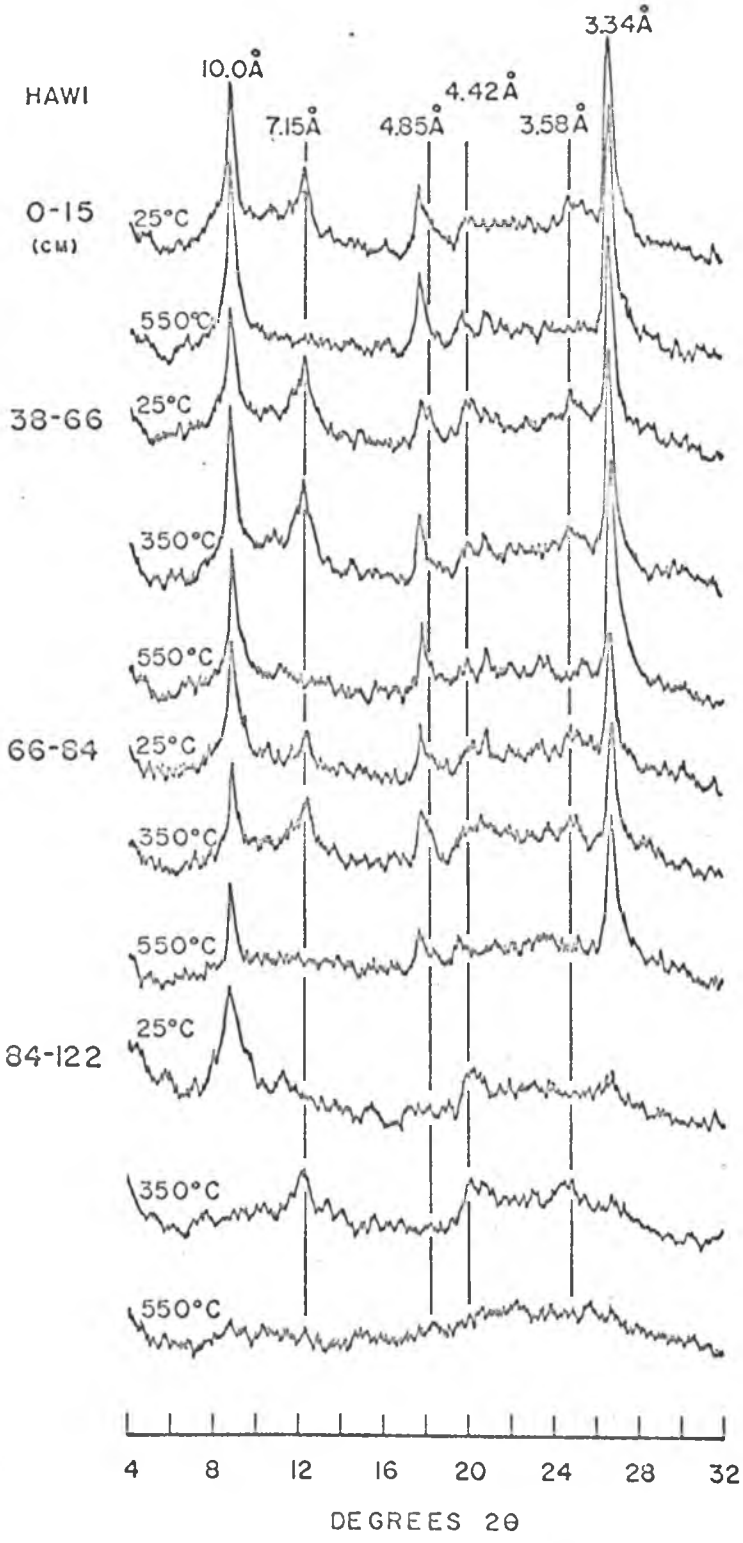


FIG. 10. X-RAY PATTERNS OF POTASSIUM-SATURATED COARSE CLAY OF THE HAWI SOIL

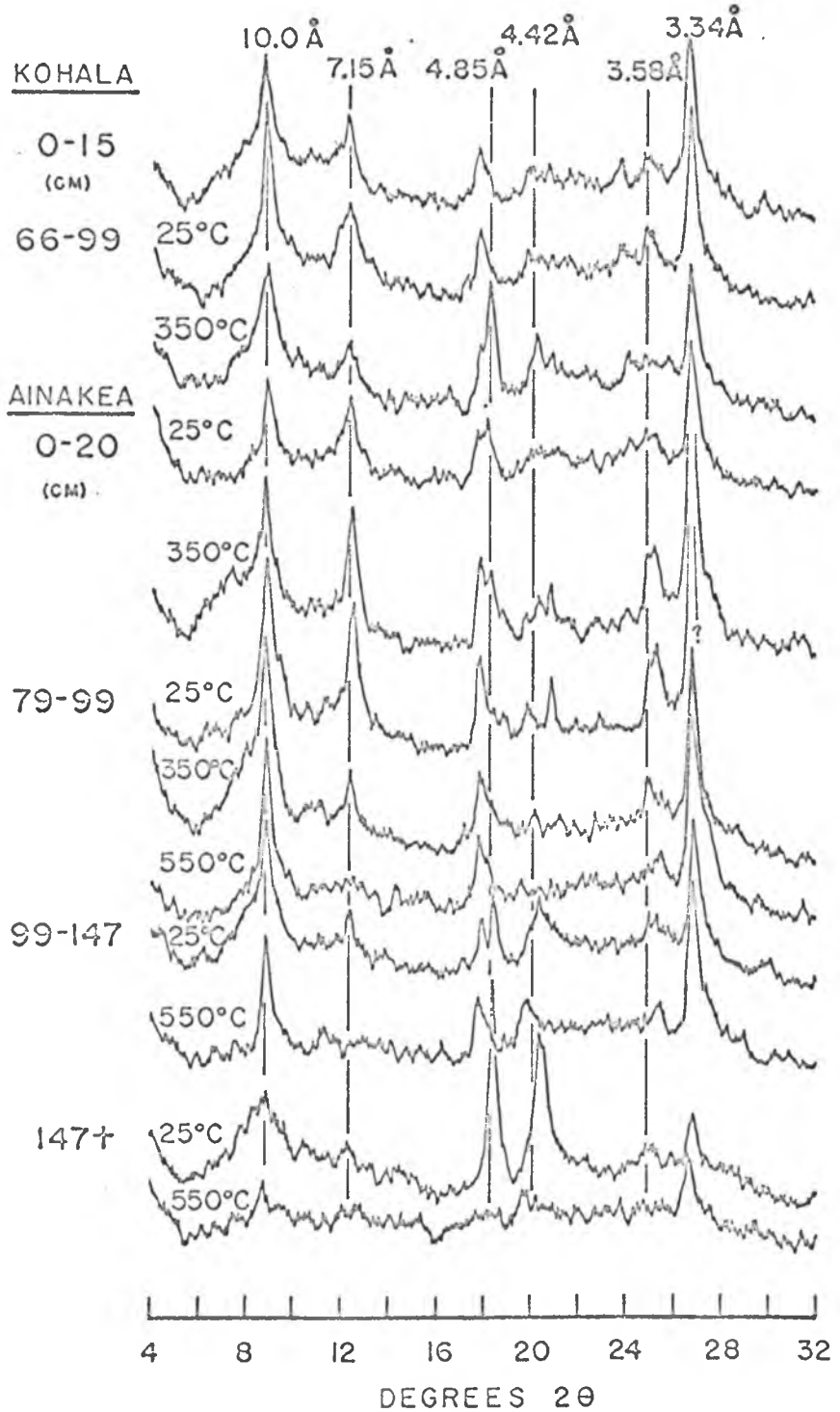


FIG. 11. X-RAY PATTERNS OF POTASSIUM-SATURATED COARSE CLAYS OF THE KOHALA AND AINAKEA SOILS

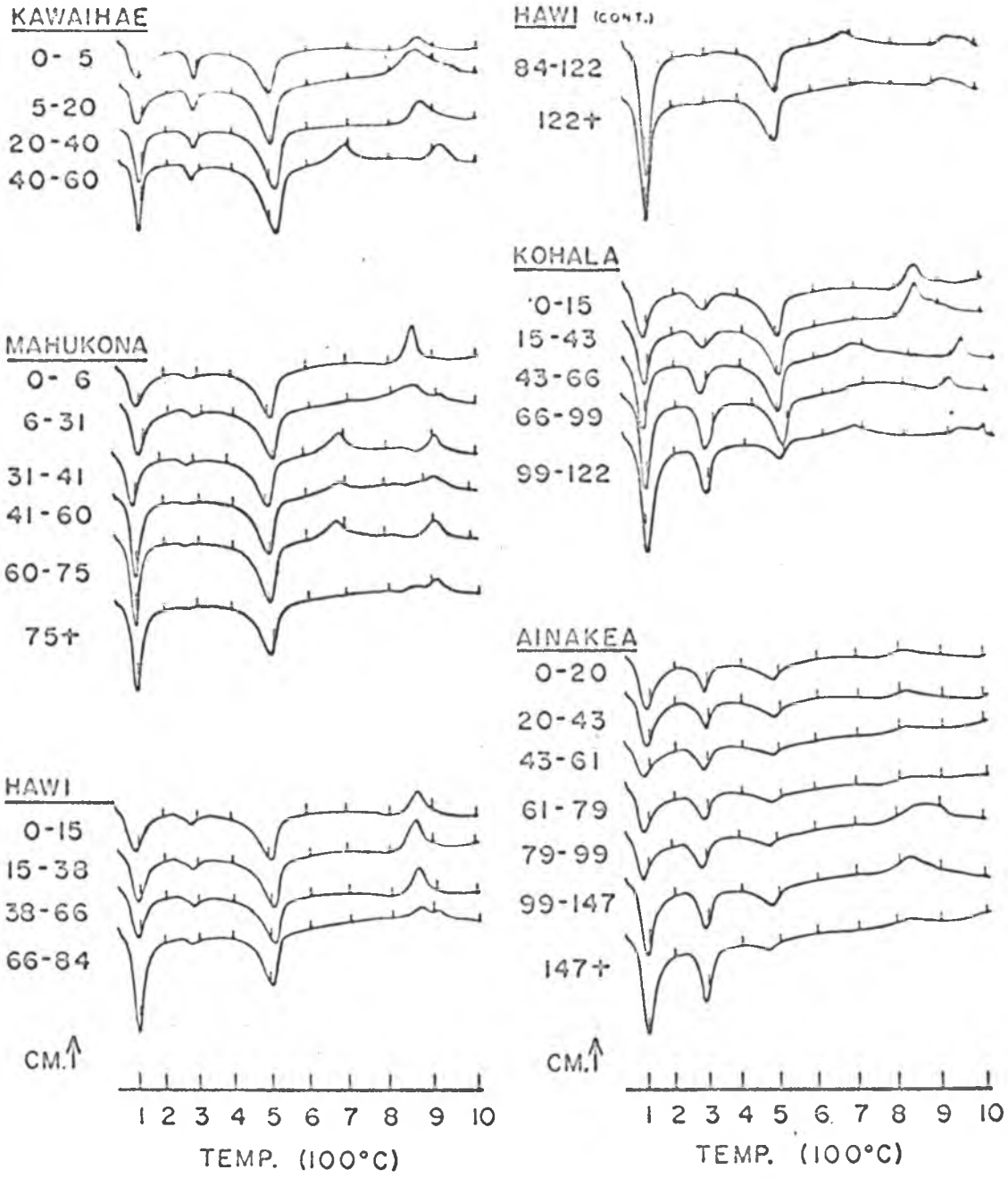


FIG 12 DIFFERENTIAL THERMAL ANALYSES OF WHOLE SOILS SHOWING TRENDS OF HYDRATION, GIBBSITE, AND KAOLINS. NITROGEN GAS SUPPRESSED OXIDATION OF ORGANIC MATTER.

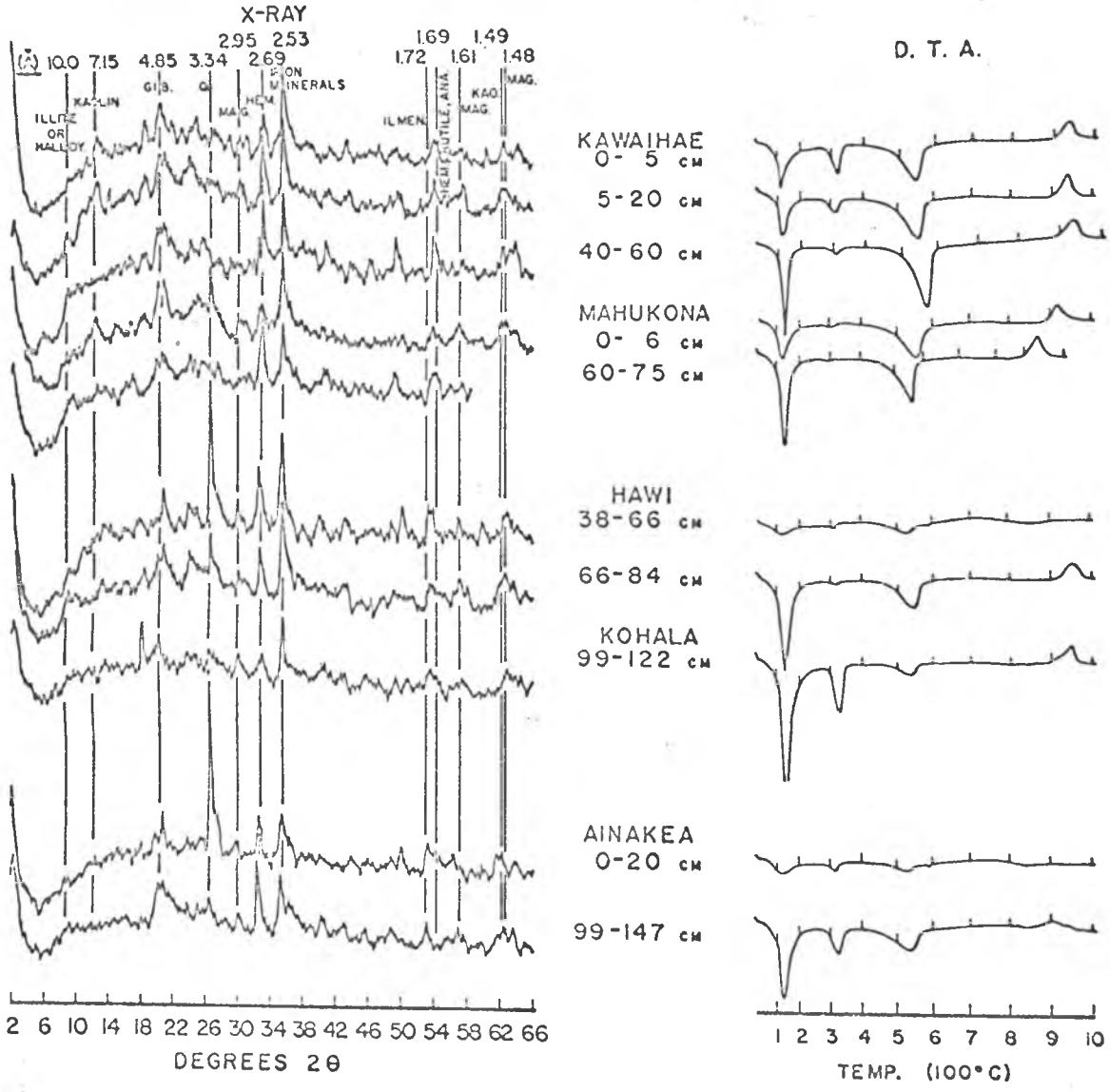


FIG. 13. DIFFERENTIAL THERMAL ANALYSES AND X-RAY PATTERNS OF SELECTED SILTS

overlooked.

Whether or not the silts contain clays which have formed within a glassy matrix or are aggregated fine clays which have become cemented together, they show two definite relationships to rainfall. One relationship is discussed in a later part of this thesis. The other relationship is the decreasing amount of kaolin found in silts with increasing rainfall.

Proposed clay weathering function for soils of less than approximately 60 inches of rainfall:

In general terms, the weathering function, calculated for the upper 40 centimeters, is based on the decreasing amount of kaolin in the silt fractions (data are not given) and the decreasing amount of kaolin with increasing rainfall (Fig. 2). For a kaolin-illite system the function is:

$$W.\ F. = \frac{\text{Total kaolin}}{\text{Dispersible clay -- Illite}}$$

In the Kawaihae soil, the amount of dispersible clay is much less than the amount of kaolin. In the soils under 27 to 45 inches of rainfall, the amount of dispersible clay and the amount of kaolin are equal. In the Ainakea soil, the amount of dispersible clay is greater than the amount of kaolin (Fig. 14).

The low percent of dispersed clay in the Kawaihae soil compared to the upper horizons of the Mahukona, Hawi, and Kohala soils is attributed to a lower degree of weathering in the Kawaihae

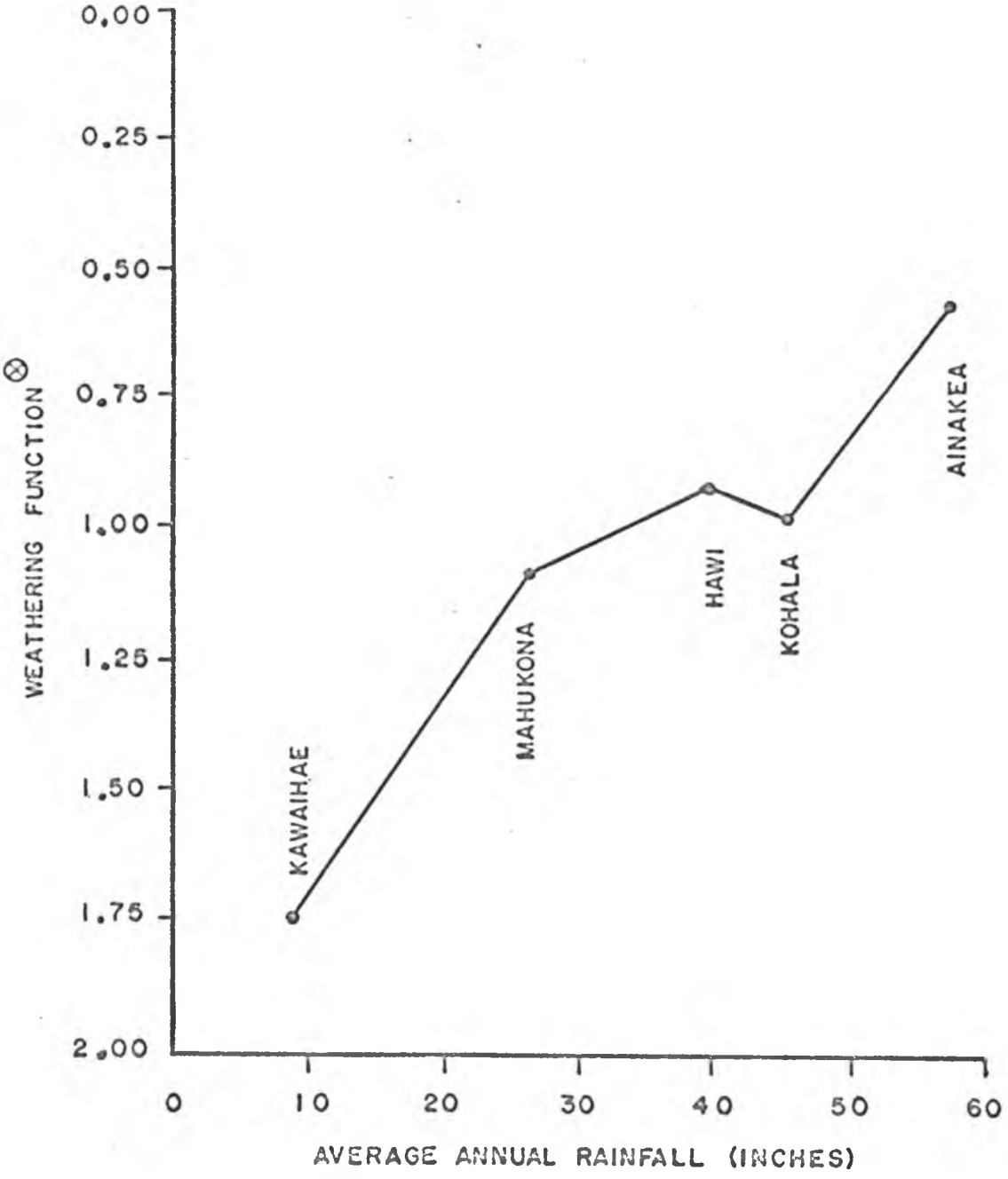


FIG. 14. RELATIONSHIP BETWEEN THE WEATHERING FUNCTION AND RAINFALL

$$\text{WEATHERING FUNCTION} \otimes = \frac{\%\ \text{KAOLIN}}{\%\ \text{DISPERSIBLE CLAY} - \%\ \text{ILLITE}}$$

soil resulting in less decomposition of the matrix or else strengthening of the cementing agent. The lesser amount of kaolin in the Ainakea soil than in the other soils is attributed to kaolin being less stable in high concentrations under the climatic condition of the Ainakea soil. The amount of dispersible clay in this soil is partly due to other secondary minerals.

Illite is subtracted from the dispersible clay since its mode of formation is quite different from that of kaolins.

Pedogenesis of illite and quartz:

Evidence is quite conclusive that both illite and quartz are formed in soils. Muscovite is not present in Hawaiian andesite or basalt (see Literature Review). It would need to be about 6 percent of the parent rock to account for 15 percent of illite in the Ainakea soil. Quartz is also not given in the rock descriptions (see Literature Review). However, a little in very small grains may be present in tholeiitic basalts (Macdonald, University of Hawaii, personal communication). It would need to be about 3 percent of the parent rock to account for its being 9 percent of the Ainakea soil (Table III). Six percent muscovite and 3 percent quartz certainly could not have been overlooked in the examination of rock specimens when minerals of 1 percent or less are reported.

Another possible source of quartz (mica, also?) is a continent such as North America. Quartz in pelagic sediments between

North America and Hawaii is postulated by Rex and Goldberg (1958) to be transported in the air from North America. If they serve as nuclei for raindrops, then quartz (and mica?) would be expected to follow a rainfall sequence. Quartz in the sediments is mostly in the range of 1 to 20 microns; quartz in the soil is mostly in the coarse clays and silts (includes 1-20 micron-size particles). However, it seems improbable that much, if any, quartz in the soils has come from the continents via air transport since silt-size quartz occurs over a meter deep in the Ainakea soil and in the Hawi soil (Fig. 13). It is doubtful that silt-size quartz could be eluviated from the surface of the Hawi soil to more than a meter deep when clay is apparently not eluviated. Movement of quartz to the lower horizons by animals or uprooted trees mixing the soil does not seem reasonable in view of the discontinuity of the discriminant function in the Ainakea soil.

Relationship of illite and quartz to rainfall:

The total amount of illite and quartz of a soil profile increases with rainfall in a manner similar to increase in depth of the profile with rainfall. In a comparison of illite with quartz, the patterns of increase with rainfall and of decrease with depth are slightly different (Table III, Figs. 15 and 16).

From Table III, increasing rainfall favors the formation of both minerals which is apparent by comparing the changes in the concentrations of these minerals in the surface horizons (Fig. 16).

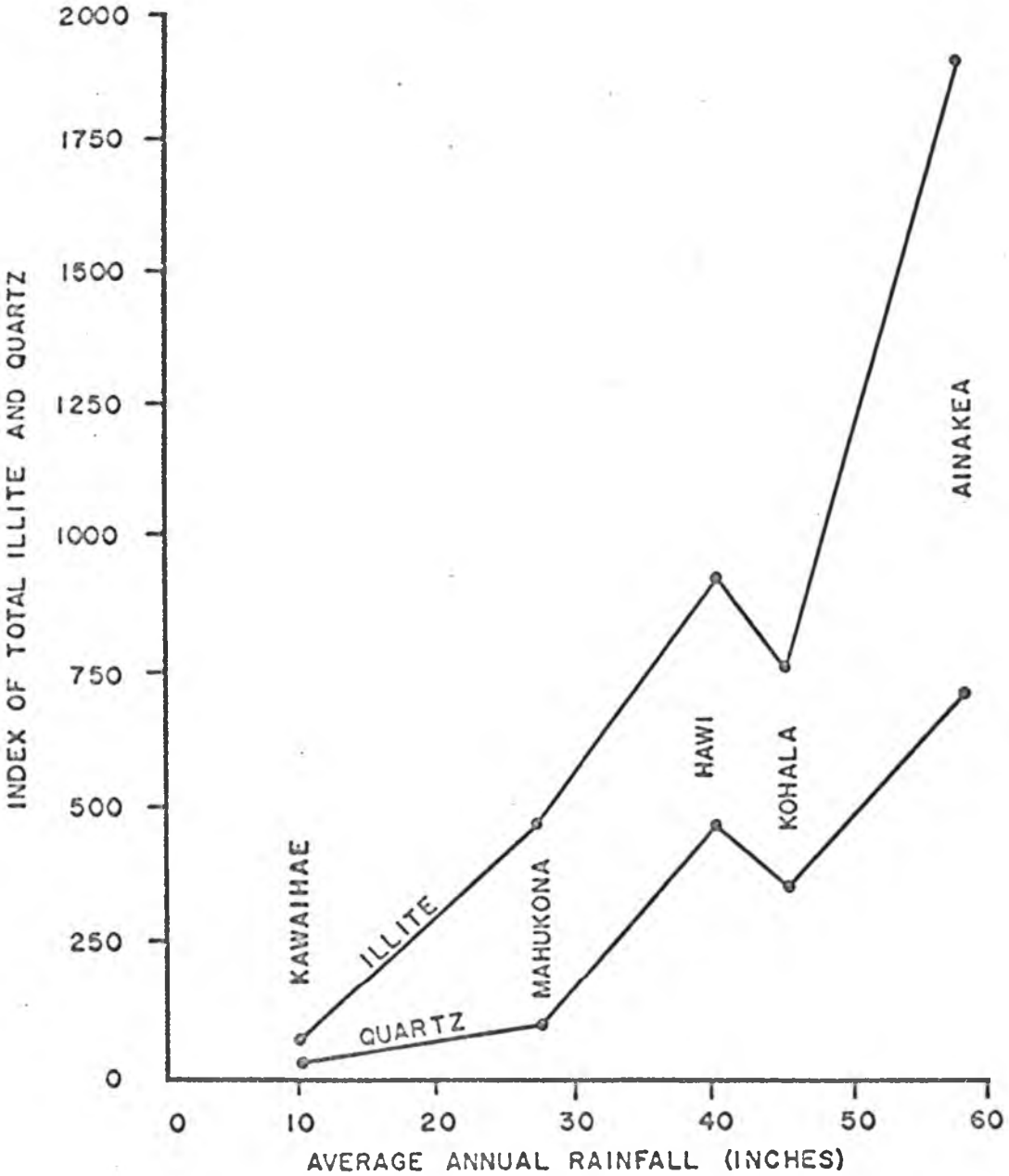


FIG. 15. COMPARISON BETWEEN TOTAL ILLITE AND TOTAL QUARTZ AS FUNCTIONS OF RAINFALL

(% ILLITE OR QUARTZ X THICKNESS OF HORIZON IN CM.)

Unlike iron, differential leaching probably does not have much influence on the concentration of quartz and illite. Their formation begins after most of the differential leaching has occurred (Fig. 2 and Table III). Quartz is well correlated with rainfall, but the shape of the illite curve (Fig. 16) indicates that illite formation is influenced by some other factor, possibly vegetation and the availability of potassium.

The trends of increasing content of illite and quartz with increasing rainfall is interrupted by the Kohala soil. The pattern of increasing depth of a fairly constant concentration of illite with increasing rainfall is also interrupted (Fig. 2). The concentration of illite begins to decrease from the surface of the Kawaihae soil, from about 31 centimeters in the Mahukona soil, from about 66 centimeters in the Hawi soil, and from about 99 centimeters in the Ainakea soil. The Kohala soil does not fit in with this pattern, and on this basis will be considered as truncated. This is far from being conclusive. The discontinuity could also be due to the possible change from the Pololu lavas to the Hawi lavas (a change in the time factor as well as parent rock). However, truncation is most likely the cause of the comparatively shallow profile.

Quartz and illite follow very similar patterns down a profile, both maintaining a fairly equal concentration to a point about half a meter above the saprolite. At this point illite shows a sharp decrease to zero or nearly zero percent, while quartz tapers off

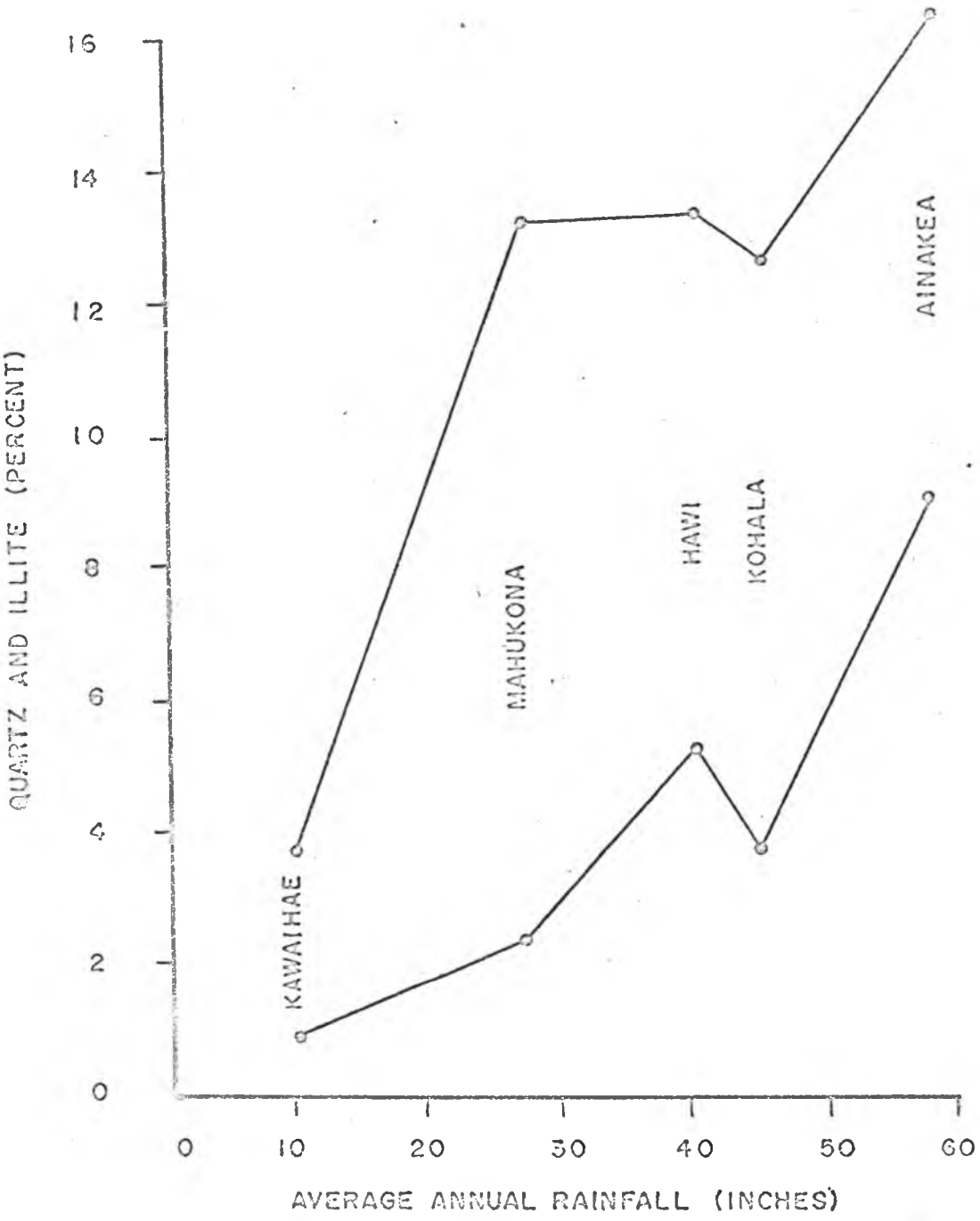


FIG. 16. COMPARISON BETWEEN RAINFALL TRENDS OF QUARTZ AND ILLITE IN THE SURFACE HORIZONS

BASED ON OVEN-DRY, ORGANIC-MATTER-FREE SOIL

to zero or nearly zero percent. In the Ainakea soil, quartz shows the same pattern as in other soils but illite shows a slight increase to a maximum in the third horizon due to illuviation.

With the exception of the Kawaihae soil, illite and quartz are probably not now forming in the surface horizons. If they were forming in the surface, they should be in much greater concentrations than in lower horizons. The active zone of formation seems to be about half a meter above the saprolite where the percents of the minerals show a sharp decrease. The potassium, which has been postulated to be recycled by vegetation, probably is in equilibrium with illite in the upper horizons. Potassium will therefore be leached through these horizons to the zone of active formation.

Gibbsite:

Gibbsite is expected to accumulate in wet climates while free iron oxides are expected to accumulate in alternating wet and dry climates. Fig. 17 shows an increase in gibbsite in the surface horizons starting from 27 inches of rainfall. The high gibbsite in the Kawaihae soil is difficult to explain. It is not a remnant of a wetter climate of the past since the free iron oxides still seem to be forming (see section on free iron oxides).

The higher gibbsite and lower illite contents of the Kawaihae soil with respect to the Mahukona soil, may indicate a relationship between these minerals. When the percent of illite is divided by 4

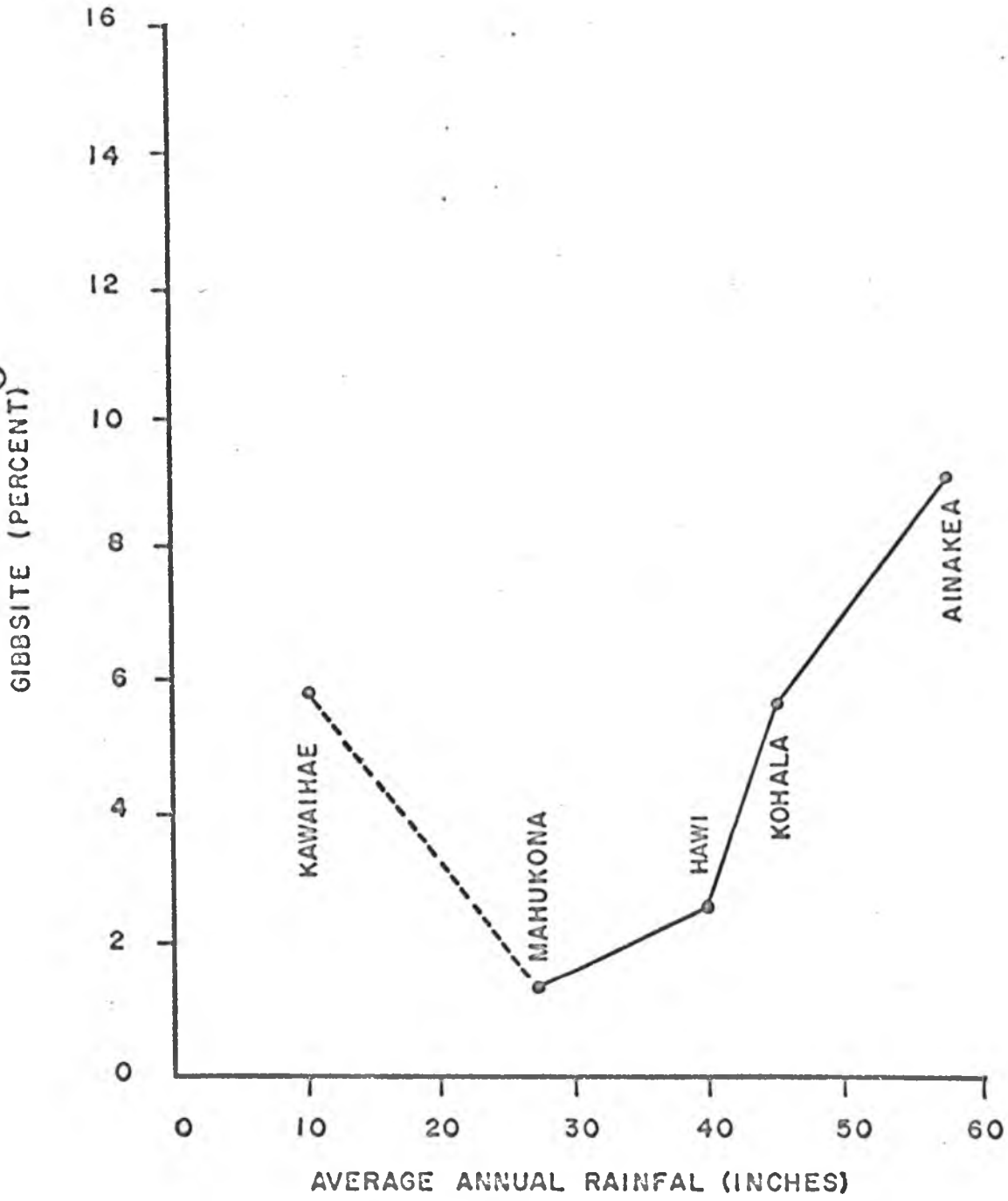


FIG. 17. GIBBSITE IN THE SURFACE HORIZONS AS A FUNCTION OF RAINFALL

⊗ BASED ON OVEN-DRY, ORGANIC-MATTER-FREE SOIL

(represents an amount of aluminum, hydrogen, and oxygen in illite equal to gibbsite) and the result added to the amount of gibbsite in the soil, the amount of calculated gibbsite is still greater in the Kawaihae soil than in the Mahukona. In view of this, the possibility of resilicating gibbsite to form illite in the Mahukona soil, cannot account for the higher gibbsite content of the Kawaihae soil compared to the Mahukona soil.

It is interesting to note that gibbsite decreases with depth in the three drier soils and increases with depth in the two wetter soils. Weathering is probably stronger in the upper horizons of the three drier soils so that gibbsite can form in them. In the wetter soils, the surface horizons are more subject to alternate wetting and drying than are the lower horizons which may seldom dry out completely. Alternate wetting and drying is less favorable than continuous wetting (perhaps also than aridness) for the formation and/or stability of gibbsite.

Chemical and Physical Properties

Relationship between cation-exchange capacity and silt:

In the discussion of the weathering function it is proposed that much of the clay seems to be tightly cemented together in the drier climates. If the clay minerals in the silts are completely coated and the matrix between the clay particles has not weathered into an active form, then it can be expected that an increasing amount of

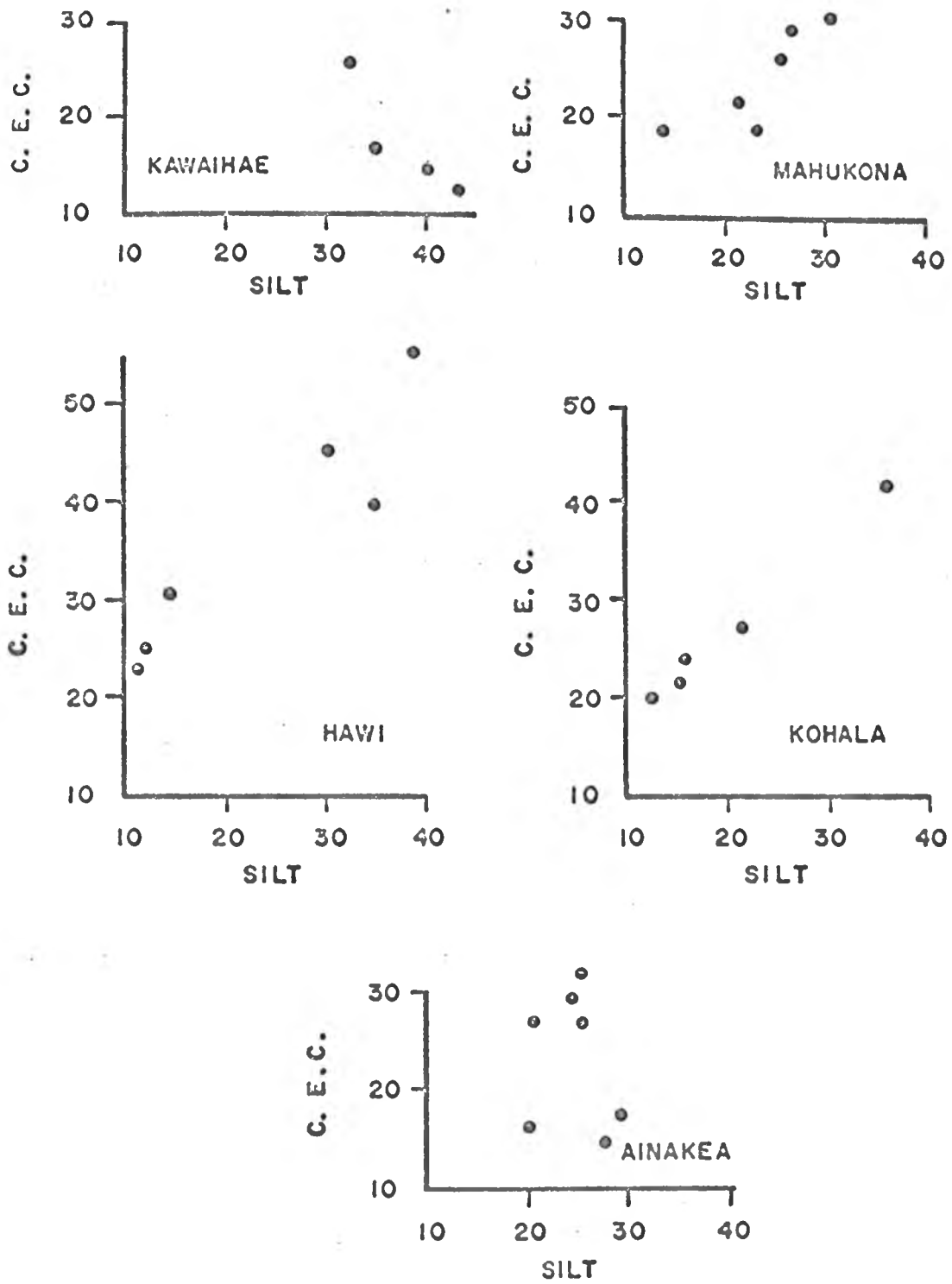


FIG. 18. INFLUENCE OF PERCENT SILT ON CATION-EXCHANGE CAPACITY AMONG HORIZONS OF EACH SOIL

silt should mean a decreasing cation-exchange capacity which is true for the Kawaihae soil (Fig. 15).

In the soils from 27-45 inches of rainfall, cation-exchange capacity increases as percent silt increases within each horizon. The silts have probably weathered so that the matrix is in an active form and also clays trapped inside have edges exposed to the soil solution for exchanging cations (Fig. 18).

The silt in the Ainakea soil seems to be quite inactive. The inactivity is probably a result of a higher degree of weathering than is found in the 27-45 inch rainfall group of soils.

Correlations between cation-exchange capacity and percent silt does not necessarily mean that the total-exchange capacity of a soil will be more or less than that of another soil. The exchange capacity of a kaolin-illite system should depend, to a large extent, on the size and amount of the clay particles.

Relationship between cation-exchange capacity and water held in air-dry soil:

The surface area of a large kaolin crystal is less than that of the same crystal broken into many pieces. In a kaolin-illite system, both cation-exchange capacity and surface area are related to the amount and size of the clay particles and therefore may be related to each other. The amount of water held in air-dry soil is probably related to the surface area within the soil and should be expected to be correlated to the cation-exchange capacity in a

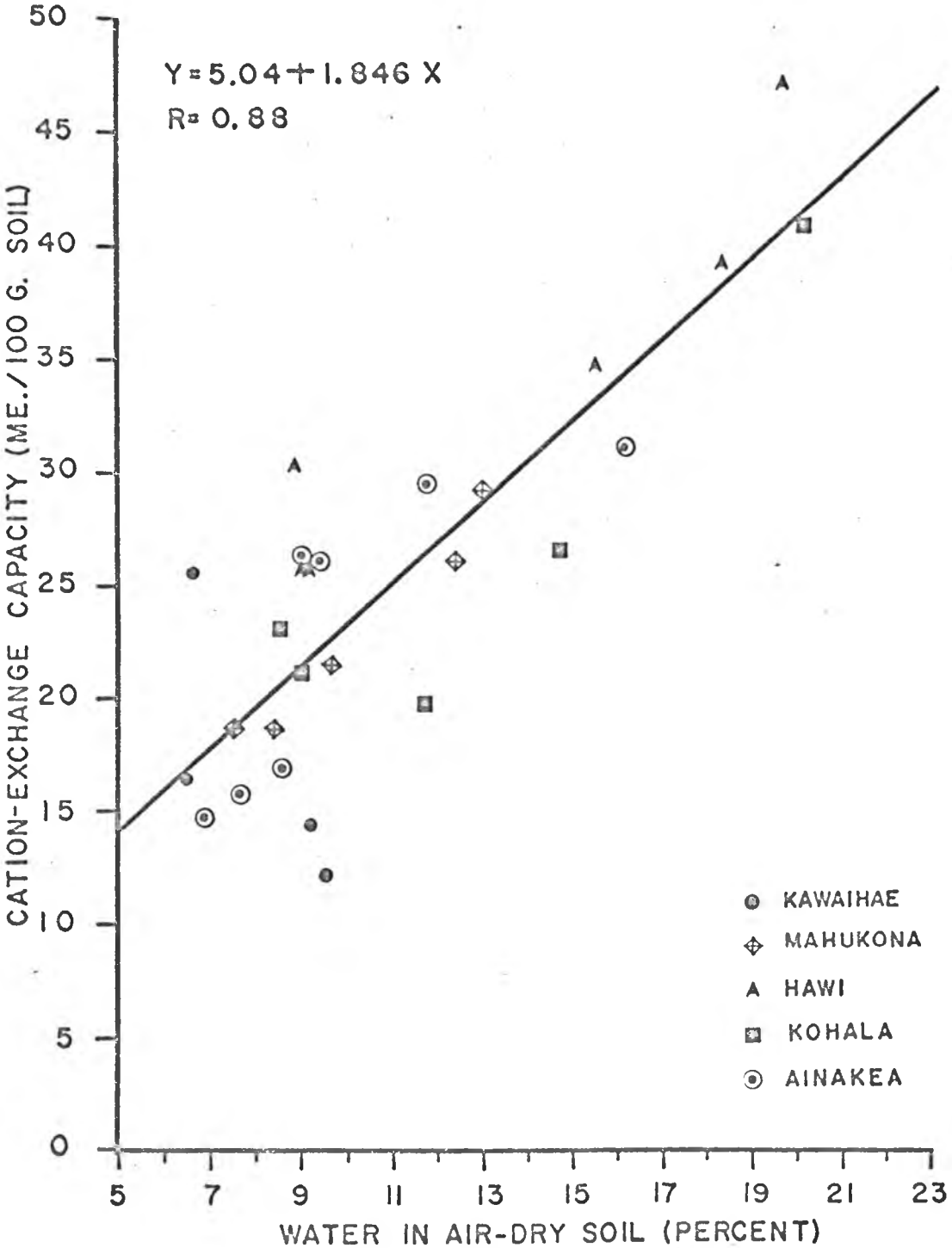


FIG. 19. RELATIONSHIP BETWEEN CATION-EXCHANGE CAPACITY AND WATER HELD IN AIR-DRY SOIL OF EACH HORIZON

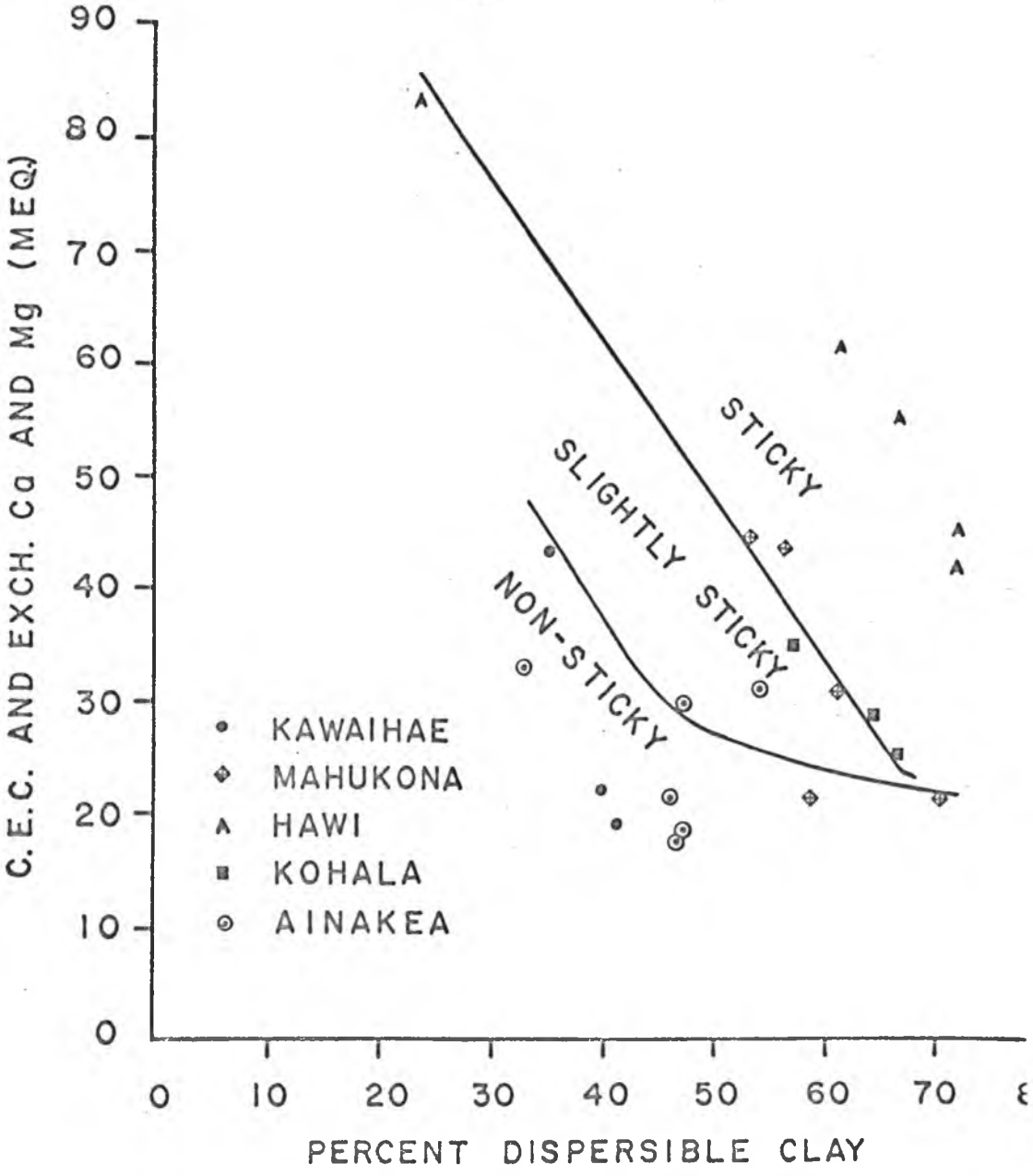


FIG. 20. GROUPING OF HORIZONS⊗ ACCORDING TO THEIR DEGREE OF STICKINESS

⊗ EXCLUDING SAPROLITIC HORIZONS.

kaolin-illite system. A very significant correlation is shown in Figure 19. This supports Jackson's (1965) statement in his discussion on surface area measurement of clays, "Evidently a balance exists between sorption energy and layer charge."

Cation-exchange capacity and stickiness:

Stickiness should also be related to the size of the soil particles. Stickiness, cation-exchange capacity, and the amount of dispersed clay in the upper half of the profiles are at a maximum in the Hawi soil under 40 inches of rainfall.

Stickiness should be caused by attraction between particles, but not by cementation of them. This attraction would depend partly on cohesion between the water films surrounding the particles. The number of water films should be related to the amount of dispersed clay. Clay size particles bound together in the silts would act as a single large particle and would contribute very little to stickiness.

Attractive forces between clay particles would depend also on the cation-exchange capacity and the type of adsorbed cations. Adsorbed divalent cations may serve as bonds between clay particles (Grim, 1953:176).

When cation-exchange capacity was plotted against percent dispersed clay, non-sticky soils were grouped separately from the slightly-sticky and sticky group. When milliequivalents of exchangeable calcium and magnesium are added to the cation-

TABLE VII. EXCHANGEABLE CATIONS, FREE SALT, AND pH

Soil Series	Depth (cm)	CEC pH=7	Ca^{++}	Mg^{++}	Na^{+}	K^{+}	Total Bases	% Base Saturation	Free** Salt	pH
			milliequivalents per 100 g							
Kawaihae	0- 5	25.5	9.6	5.2	0.50	1.5	16.8	66	0.43	6.1
	5- 20	16.3	4.0	1.9	0.67	1.0	7.6	46	0.21	5.8
	20- 40	14.5	3.0	1.9	1.0	1.7	7.6	52	0.15	5.9
	40- 60	12.1	3.0	2.7	1.6	0.64	8.0	66	0.21	6.4
Mahukona	0- 6	18.6	2.8	0.36	0.58	1.9	5.6	30	0.51	5.5
	6- 31	18.6	2.8	0.43	0.85	1.7	5.8	31	0.39	5.8
	31- 41	21.5	3.4	6.4	2.1	1.1	13.0	60	0.54	6.4
	41- 60	29.3	6.5	9.3	7.6	0.62	24.0	82	1.5	6.9
	60- 75	26.1	7.8	10.2	9.3	1.1	28.4	109	2.8	7.1
	75+	30.5	18.1	11.6	9.8	1.4	40.9	134	3.7	7.1
Hawi	0- 15	30.4	16.3	9.5	0.73	3.8	30.3	100	0.60	6.8
	15- 38	25.0	9.6	8.2	0.91	2.8	21.5	86	0.39	6.6
	38- 66	25.9	11.2	9.1	1.2	1.7	23.2	89	0.55	6.8
	66- 84	34.9	17.4	10.3	3.7	1.7	33.1	95	0.65	7.3
	84-122	45.4	25.1	13.2	6.1	0.39	44.8	99	0.71	7.7
	122+	39.5	19.1	13.9	7.9	0.14	41.1	104	1.1	7.5
Kohala	0- 15	23.9	9.1	0.44	0.70	2.2	12.4	52	0.29	6.0
	15- 43	21.4	7.5	0.31	1.3	0.64	9.8	46	0.16	5.9
	43- 66	19.7	5.7	0.25	1.7	0.96	8.7	44	0.11	5.9
	66- 99	27.1	7.9	0.31	1.5	0.88	10.6	39	0.14	5.8
	99-122	41.7	13.2	0.44	0.78	0.49	14.9	36	0.18	6.4
Ainakea	0- 20	26.7	3.2	0.16	0.26	0.90	4.6	17	0.49	4.8
	20- 43	26.6	4.6	0.21	0.42	0.58	5.8	22	0.41	5.1
	43- 61	17.3	4.2	0.16	0.54	0.11	4.9	28	0.31	6.0
	61- 79	14.6	3.3	0.14	0.46	0.10	4.0	27	0.31	5.9
	79- 99	15.9	2.9	0.13	0.42	0.12	3.6	23	0.46	5.6
	99-147	29.4	3.6	0.30	0.92	0.10	5.0	17	0.68	5.1
	147+	31.6	1.4	0.16	0.84	0.06	2.4	8	0.86	5.2

exchange capacity, the slightly sticky and sticky soil horizons were separated from each other (Fig. 20). This assumes that the effect of the two divalent cations is equal to the effect of the cation-exchange capacity which may or may not be true.

Exchangeable cations:

The base saturation does not decrease with increasing rainfall as expected. The highest base saturation was expected to be in the Kawaihae soil under 10 inches of rainfall. The highest base saturation is in the Hawi soil under 40 inches of rainfall. The Hawi soil, Kohala soil, and the Ainakea soil fall into the expected pattern of decreasing base saturation with increasing rainfall (Table VII).

In attempting to explain the interruption of the sequence by salinity in the lower horizons of the Mahukona soil and by the high base saturation of the Hawi soil (Table VII), three sources of cations must be considered: the ocean with air as the transporting agent, the weathering of primary minerals, and seepage water which could be imperceptible to the eye.

In considering the ocean, an explanation is necessary for the lack of salinity in the Kawaihae soil which is closer to the ocean than is the Mahukona sample site.

In considering the rate of weathering relative to the rate of leaching, an explanation is needed for the low exchangeable calcium and magnesium in the upper 30 centimeters of the Mahukona soil

(less than 20 percent) and the high exchangeable calcium and magnesium (more than 70 percent) in the Hawi soil.

In considering seepage water, the presence of seepage water should be shown to exist even if for only brief periods of the year. At the very least, an impervious or slightly pervious layer should be shown to underlie the Mahukona and Hawi soils.

The salinity of the Mahukona soil is a problem that needs further investigation. It could present a problem in the event that this area or an area at slightly higher elevation is ever brought under irrigation.

Other problems for future research:

The shallowness of the Kohala soil needs to be more closely examined. If it is losing soil from the surface by erosion, soil conservation practices might be considered desirable.

The agronomists might be interested in investigating how liming a soil will affect the natural supply of potassium. It appears that illite is in equilibrium with the soil solution in view of its fairly constant concentration in the upper horizons of the deep soil profiles. In a system in which kaolin and potassium mica are in equilibrium (Garrels and Christ, 1965), a decrease in the H^+ ion concentration should cause a corresponding decrease in the K^+ ion concentration in order to maintain the equilibrium.

From the soil genesis point of view, several problems present themselves. The presence of gibbsite in the Kawaihae soil

needs to be explained, the sharpness of the boundary between the Kohala and Hawi soils needs to be explained in view of the fact that the rainfall difference is only 5 inches, and the sequence should be continued into higher rainfall regions at the same elevation. There are many other sequences in the Kohala Mountain from which soil genesis information could be gathered concerned with the effect of temperature, climate, slope, etc.

CONCLUSIONS

1. In agreement with other workers who have studied the weathering process in Hawaiian soils, desilication is a major soil-forming process. Most of the desilication occurs during the formation of the saprolite or soil in the saprolitic horizon. The equal concentration of total iron throughout a profile indicates that the loss of SiO_2, MgO, CaO, and Na_2O occurs very early in the formation of the soil, before quartz or illite begins to be formed.

2. The increase in percent of free iron oxides with increasing intensity of weathering due to increasing rainfall is probably not due to a greater amount of formation of free iron oxides. The concentration of resistant iron minerals (not reduced with dithionite) is similar in the surface and saprolitic horizons when total iron is set equal to 25 percent of the soil, in spite of the more intense weathering in the surface horizon. Under 10 inches of rainfall, the resistant iron minerals increase with depth, which is an indication that free iron oxides are still being formed in that soil. The ineffectiveness of increasing rainfall on the formation of free iron oxides can also be seen by comparing three surface horizons, under 27, 45, and 57 inches of rainfall, respectively, and having similar parent rock according to their discriminant functions. (The discriminant function uses zirconium and nickel to determine the basaltic or andesitic nature of the

parent rock.) When total iron, expressed as Fe_2O_3, is adjusted to 25 percent of the soil, the amount of resistant iron is approximately the same for the three surface horizons. This reasoning assumes similar amounts of the same types of iron bearing minerals in the parent rock.

3. The increasing concentration of free iron oxides (average percent in a soil profile) shows an inverse relationship to the amount of kaolin. This suggests that the increased concentration is due to the loss of silica which would have been in the kaolin structure. The lower kaolin content in soils under higher rainfall does not necessarily mean that kaolin is now being, or has been, decomposed.

4. It appears that arid conditions favor the strong cementation of kaolin particles and on this basis a weathering function has been proposed for soils of less than 60 inches of rainfall. The kaolins in the silt fractions may have formed within a matrix of volcanic glass which has not yet been weathered enough, especially in the drier regions, to release the clays into the clay fraction. Alternatively, dispersible clays may have become cemented together in a matrix which is more stable in arid conditions. The proposed weathering function is calculated for approximately the upper 40 centimeters of the soil and equals the average percent of kaolin divided by the percent dispersible clay minus the percent illite.

5. The strong cementation of clays in the silt of a soil under 10 inches of rainfall probably has caused the silt to be inactive. As the percent of silt in the horizons of a low-rainfall soil increases, the cation-exchange capacity decreases. The silts in the soils under 27-45 inches of rainfall seem to have weathered into an active form. A greater percent of silt in a horizon generally means a greater cation exchange capacity compared to other horizons within the same profile. Under a 57-inch rainfall, the silt has apparently weathered into a slightly active form which does not noticeably affect the cation exchange capacity of any horizon compared to the other horizons.

6. The amount of dispersible clay in the upper 40 centimeters of the soils is maximum under 40 inches of rainfall. Cation exchange capacities and stickiness are also maximum under 40 inches of rainfall. The horizons, excluding the saprolitic horizons, can be grouped according to their being non-sticky, slightly sticky, or sticky by plotting the sum of the cation exchange capacity, exchangeable calcium, and exchangeable magnesium against the percent of dispersible clay of each horizon.

7. In addition to using the concentration of free iron oxides and the weathering function, as indications of the degree of weathering of a soil, the amount and pattern of illite and quartz can also be used. The total amounts of quartz and illite increase with increasing rainfall. Also, their concentrations in the surface

horizons increase with rainfall. None of their increases is due to the same factors which cause the increase in total iron. Illite and quartz begin to form after iron has become concentrated. The increase of quartz in the surface horizons shows a much closer correlation with rainfall than does that of illite possibly due to the availability of potassium required for the formation of illite.

8. Both quartz and illite are probably pedogenic. Neither is found in any significant amounts in the basaltic and andesitic rocks of the Kohala Mountain. It is also doubtful that they have come from the continents via the atmosphere because of the occurrence of silt-size quartz more than a meter deep in the Hawi and Ainakea soils (40 and 57 inches of rainfall, respectively). Gradual mixing of the soil is probably not the answer since the Ainakea soil has a discontinuity in the zirconium and nickel contents. It is doubtful that silt size particles would be eluviated from the surface to a depth of one meter. In addition, there is no accumulation of either quartz or illite in the surface horizons. In fact, the distribution of both is fairly uniform to a depth of approximately half a meter above the saprolitic horizon.

9. The pattern of illite along with the shallow depth of the soil at the Kohala site (45 inches of rainfall) compared to that at the Hawi site under 40 inches of rainfall, suggests that the Kohala soil at the sample site, if not in general, may be truncated by as much as half a meter. The high gibbsite and free iron oxide

contents indicate that it is more highly weathered than the Hawi soil. This indicates that a possible change in the parent rock between the Pololu and Hawi volcanic series may be partly the cause of the discontinuity between the Hawi soil (Pololu volcanic series) and the Kohala soil. Soils from the Hawi volcanic series are also geologically younger if erosion is negligible.

10. An incidental result of this investigation is the correlation between cation-exchange capacity and water held in air-dry soil ($r=0.88$). Both properties are related to the size and amount of clay in the kaolin-illite system. Small clay particles mean more broken edges for exchange sites and more surface area to hold the water.

11. Some very unexpected results of this investigation is the interruption of the sequence by salinity in the lower horizons of the 27-inch rainfall soil, the 100-percent base saturation of the Hawi soil without salinity, and the less than 70-percent base saturation of the 10-inch rainfall soil without salinity although it is closest to the ocean. Seepage water is not known to be present under the 27- and 40-inch rainfall soils. A theory using the relative rates of weathering and leaching would need to account for the low exchangeable calcium and magnesium in the upper part of the soil in the 27-inch rainfall zone and the high exchangeable calcium and magnesium in the soil of the 40-inch rainfall zone.

Further investigations are necessary to determine the reasons for salinity and the unexpected high base saturation of the kaolin soils.

SUMMARY

The single factor effect of climate, expressed by annual rainfall, on the genesis of soils formed from andesite and basalt has been studied using soils from the Kohala region.

Although the sequence is interrupted by salinity and a change in volcanic series (change in the time factor of soil formation), several trends still can be noticed. Free iron oxides, total amount of illite, total amount of quartz, illite in the surface horizons, quartz in the surface horizons, and gibbsite (under more than 27 inches of rainfall) increase with increasing rainfall between 10 and 27 inches annually.

The increase in free iron oxides is due to the loss of other ions from the parent rock during the formation of the saprolite. The concentrations of free iron oxides shows an inverse relationship to kaolin with increasing rainfall. It appears that the increase in free iron oxides with increasing rainfall above 27 inches is not due to a greater amount of formation of them. However, the increase in illite and quartz is probably due mainly to a greater amount of formation in the wetter rainfall regions.

The amount of dispersible clay in the upper 40 centimeters, cation-exchange capacity, and stickiness show a maximum in the 40-inch rainfall zone. The stickiness of each horizon, excluding the saprolitic horizons, can be grouped into non-sticky, slightly

sticky, and sticky by plotting the sum of cation exchange plus exchangeable calcium and magnesium against percent of dispersible clay.

Cation-exchange capacity shows a positive correlation with silt in the 27- to 45-inch rainfall zone. The matrix of the silt in the 10-inch rainfall zone has probably not weathered to a stage of activity and the silt in the 57-inch rainfall zone has probably weathered into a stage of low activity. The increasing weathering of the silt is part of the theory behind the proposed weathering function. The function is calculated by dividing the average percent of kaolin in the upper 40 centimeters by the average percent of dispersible clay from which illite has been subtracted.

An incidental result of the investigation is the very significant correlation between cation-exchange capacity and the amount of water held in air-dry soil.

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